

# Status of NOvA



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# Outline



- Open Questions in Neutrino Oscillations
- Overview of NOvA
- NuMI Beam
- NOvA Status
- NOvA Sensitivities



# What Next?



$$U = \begin{matrix} \text{Atmospheric} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \end{matrix} \times \begin{matrix} \text{Cross Terms} \\ \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \end{matrix} \times \begin{matrix} \text{Solar/KamLAND} \\ \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{matrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$$

- Despite success of current experiments, many questions remain about oscillations
  - Is the PMNS matrix sufficient to explain oscillations?
  - Are there more neutrinos than the 3 active flavors?
  - What is the size of  $U_{e3}$ ?
  - Is the CP violating phase non-zero?
  - What is the mass hierarchy?





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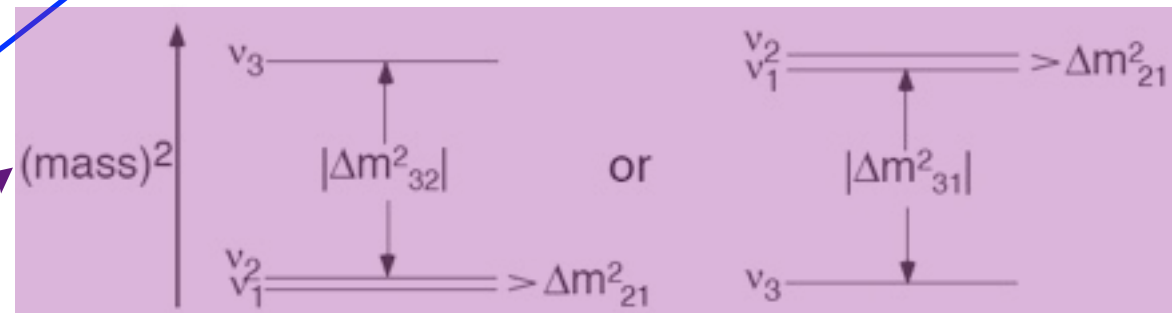
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- Is the PMNS matrix sufficient to explain oscillations?
- Are there more neutrinos than the 3 active flavors?
- What is the size of  $U_{e3}$ ?
- Is the CP violating phase non-zero?
- What is the mass hierarchy?

$\nu_4, \nu_5, \dots?$

$\theta_{13} \neq 0?$

$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$

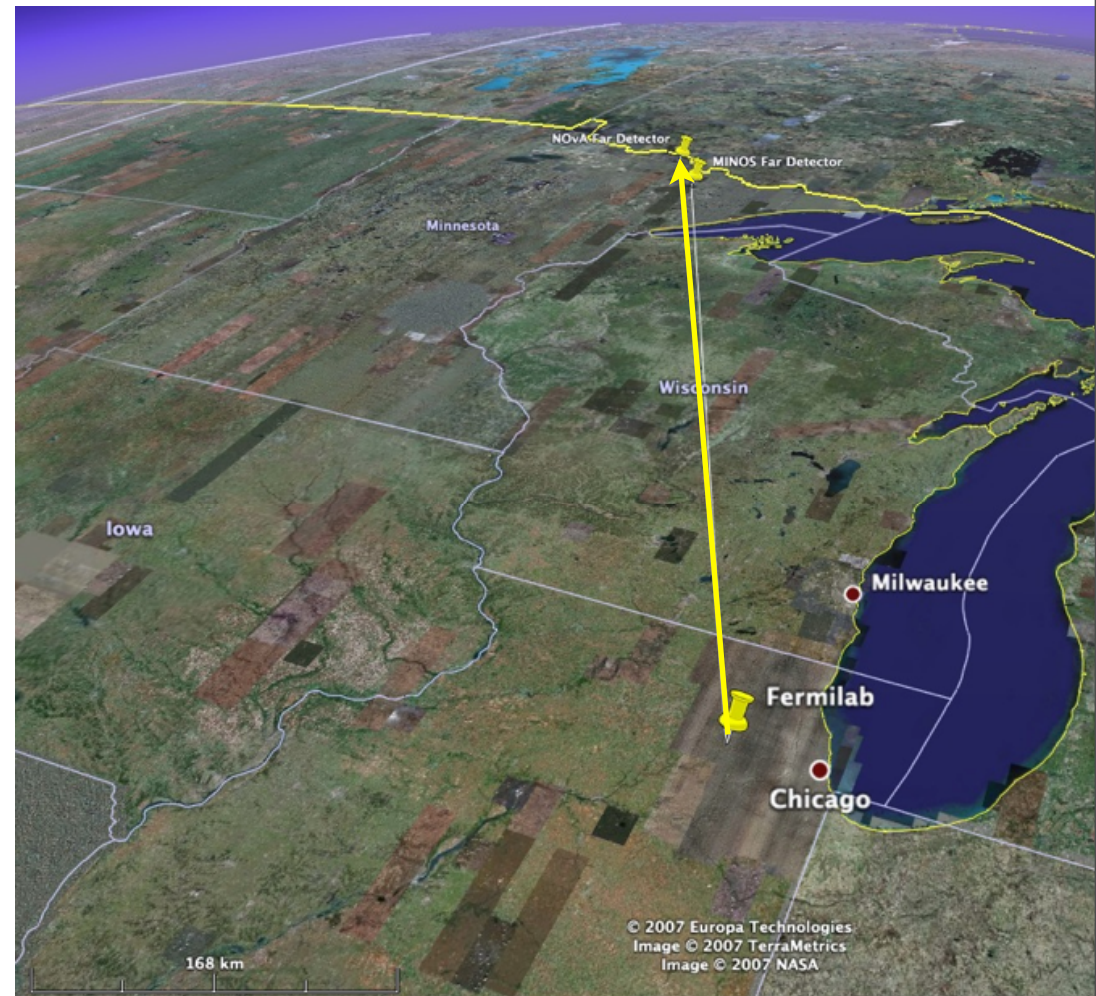




# NOvA



- NOvA is a 810 km baseline neutrino experiment
- Searching for  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations
- Use near detector to understand beam at source, far to look for oscillations
- Physics goals include
  - Measurement of  $\theta_{13}$
  - Determining the ordering of mass hierarchy
  - Measure  $\delta$  - CP violating phase
- Use equal exposures for  $\nu$  and  $\bar{\nu}$

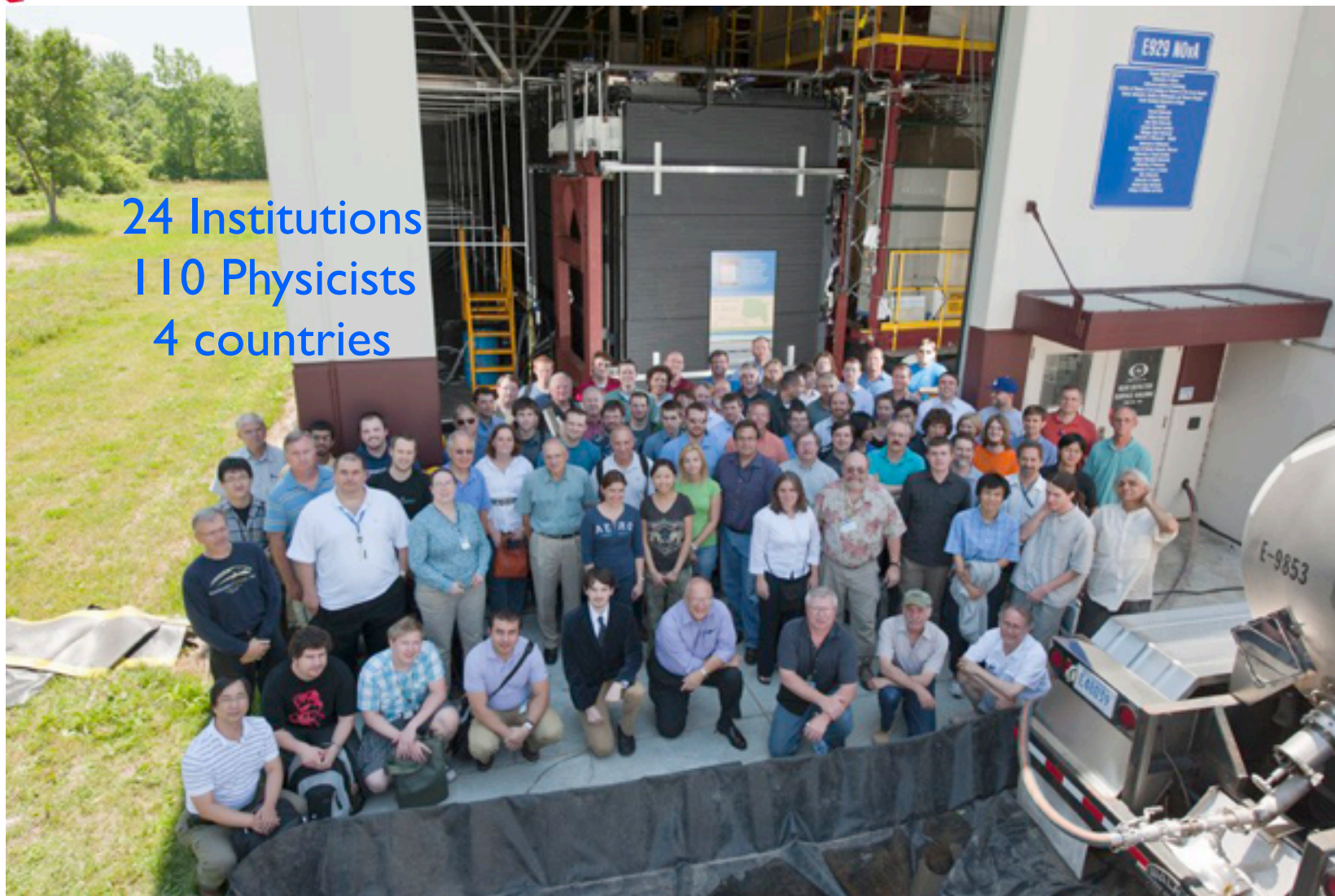




# NOvA Collaboration



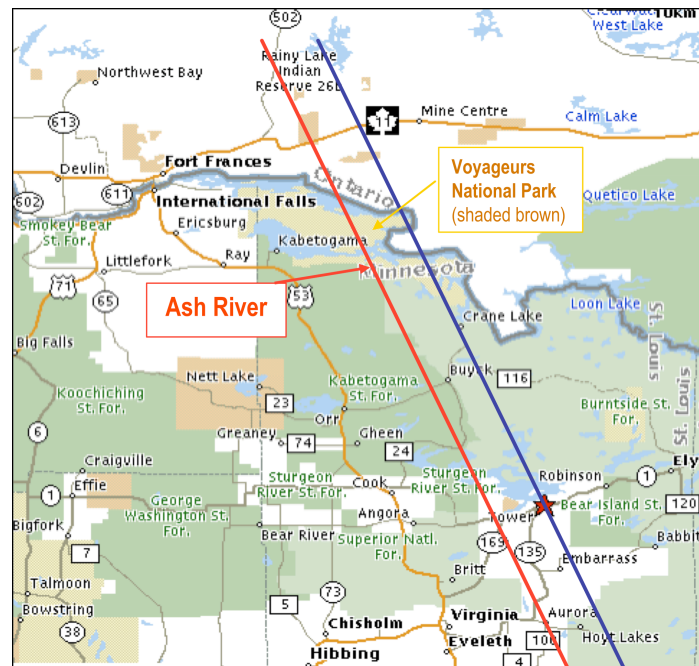
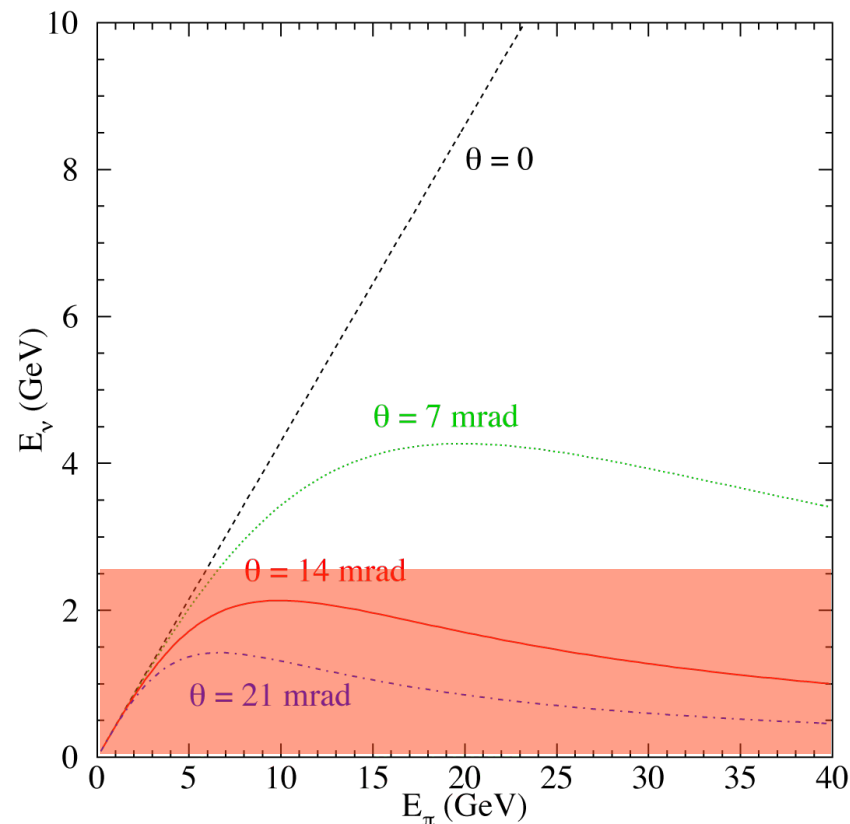
24 Institutions  
110 Physicists  
4 countries



Argonne, Athens, Caltech, Institute of Physics of the Czech Republic, Charles University, Czech Technical University, Fermilab, Harvard, Indiana, Iowa State, Lebedev Physical Institute, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, South Carolina, SMU, Stanford, Tennessee, Texas-Austin, Tufts, Virginia, William and Mary, Wichita State



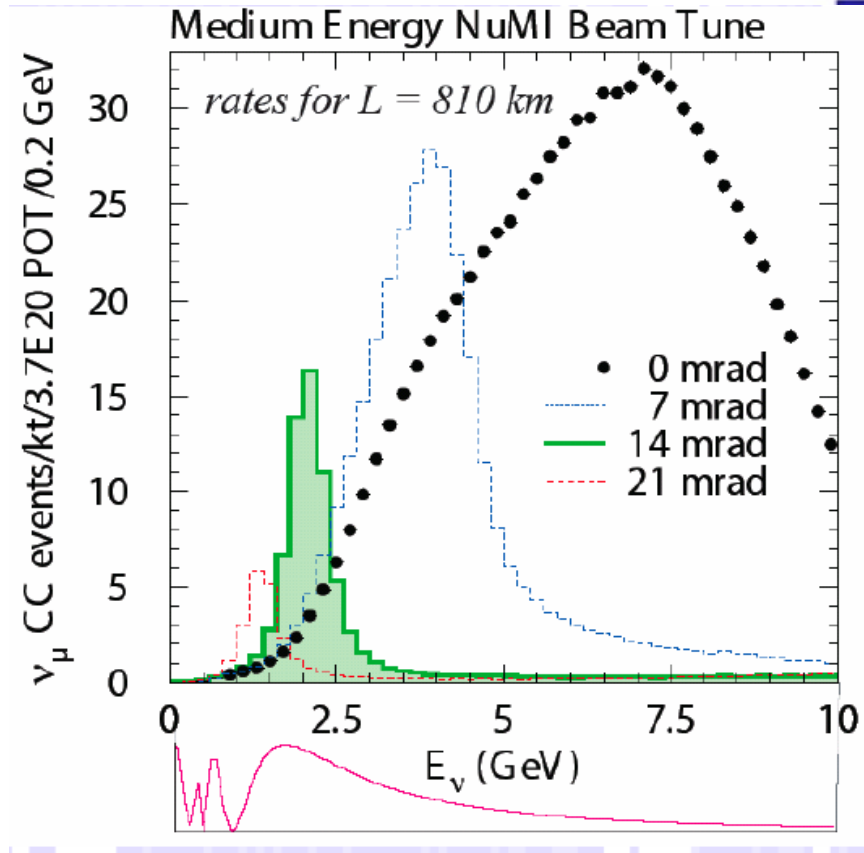
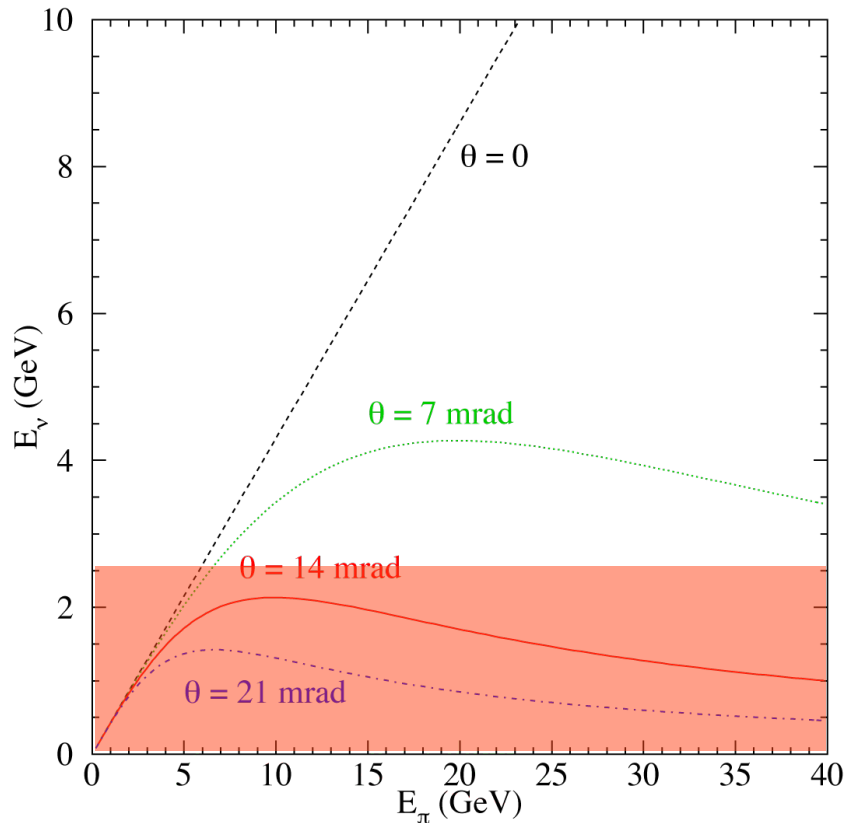
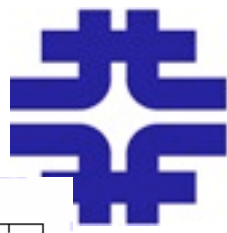
# Off-Axis Beam



- Placing detector off axis exploits decay kinematics to produce a narrow band beam
- 14 mrad off-axis produces a narrow band beam peaked  $\sim 2.2$  GeV to maximize oscillation probability
- Almost no high energy tail, reduces feed down from neutral current interactions



# Off-Axis Beam



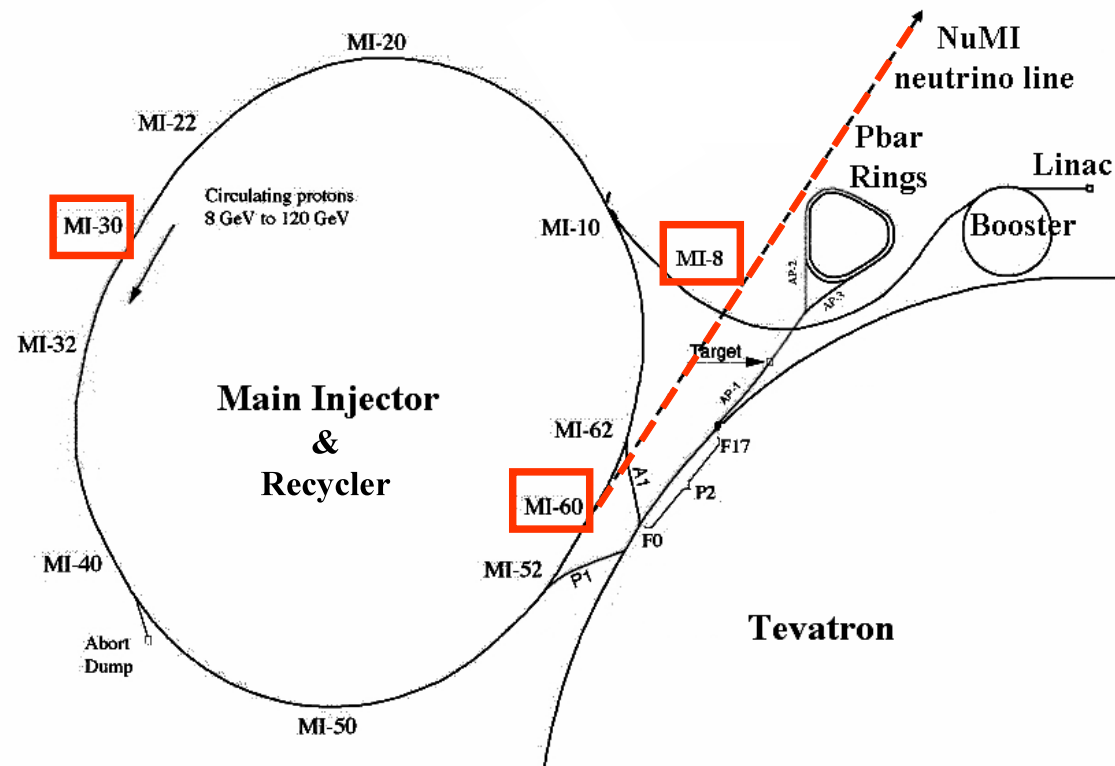
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# Accelerator Upgrades

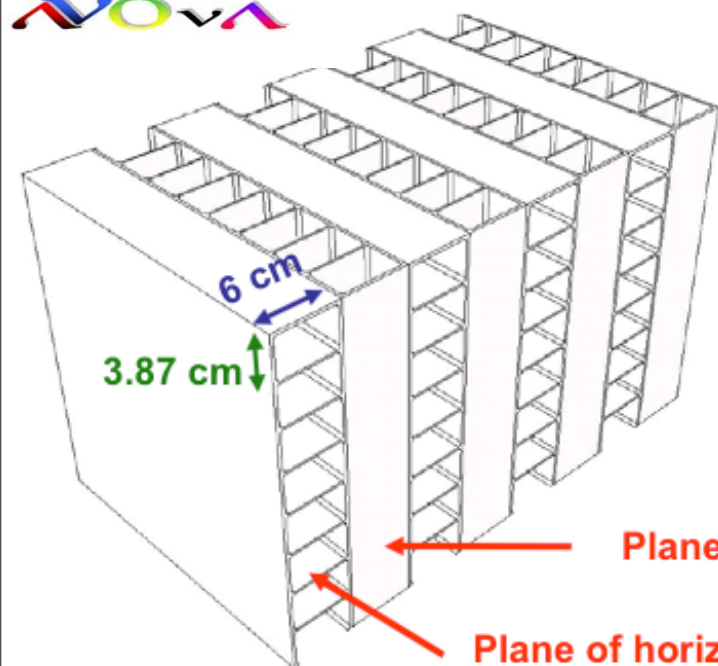


- Plan is to increase beam power from 300 kW to 700 kW using existing complex
- Lower cycle time to 1.33 seconds by slip stacking in the Recycler
- Increase intensity per cycle using new injection kicker to allow 12 Booster instead of 11
- Upgrade target, horn 1, etc

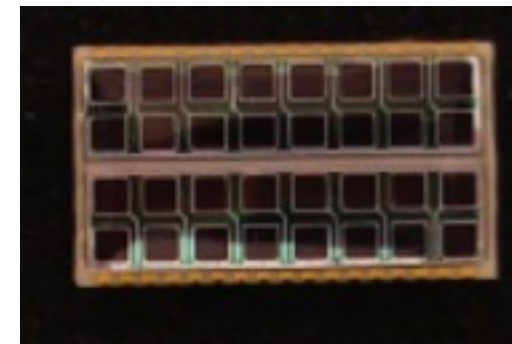




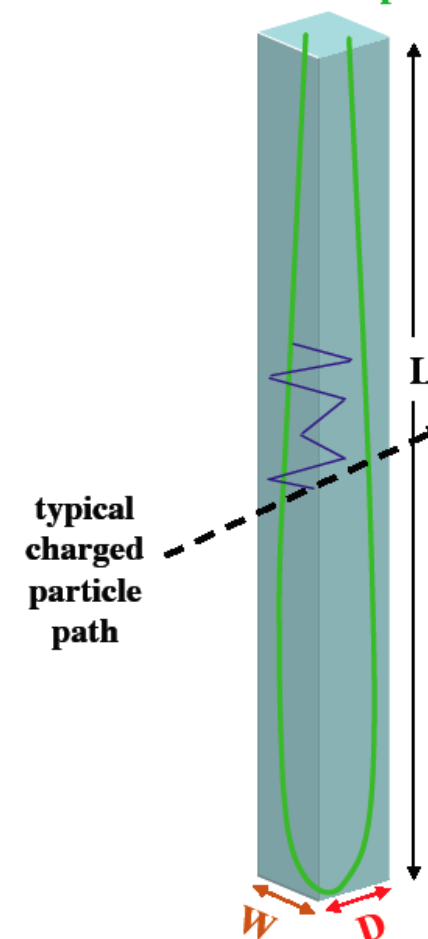
# Active Detector Element



> 368,000 cells in FD  
~12,000 km fiber in FD  
0.15  $X_0$  sampling per plane

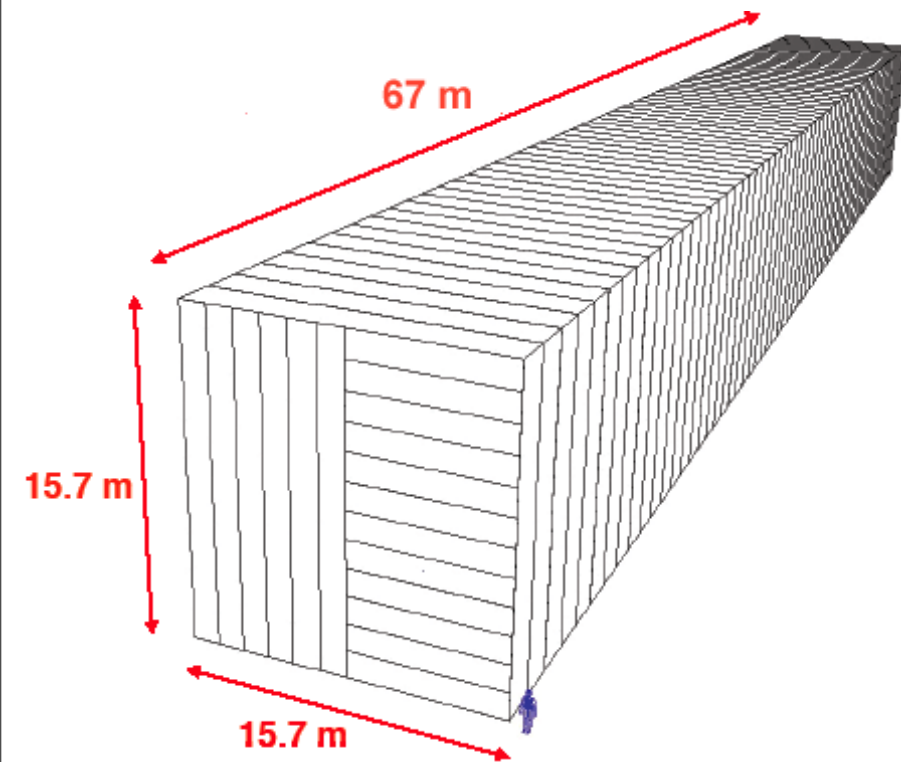


To 1 APD pixel



- Basic element is a PVC extrusion with 15%  $\text{TiO}_2$  to increase reflectivity
- Extrusions filled with liquid scintillator - mineral oil with 5% pseudocumene and some wave shifters, ~30 PE at far end from scintillator
- Scintillator light delivered to APD using WLS fiber
- Avalanche Photo Diodes (APD) used to detect scintillation light

# Far Detector



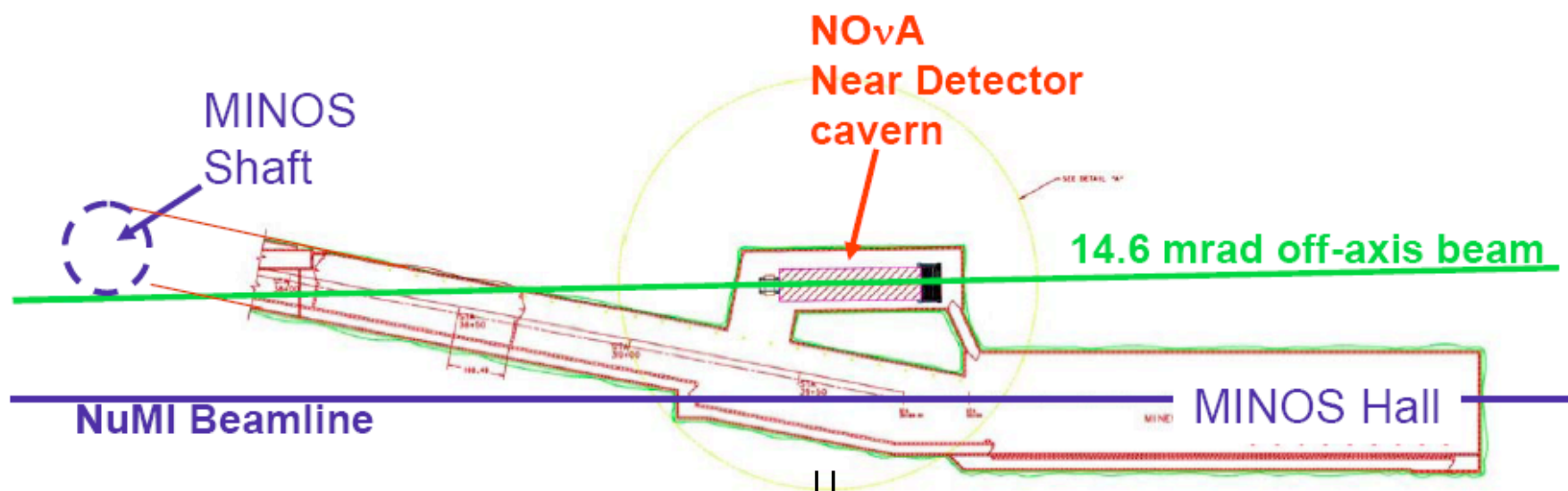
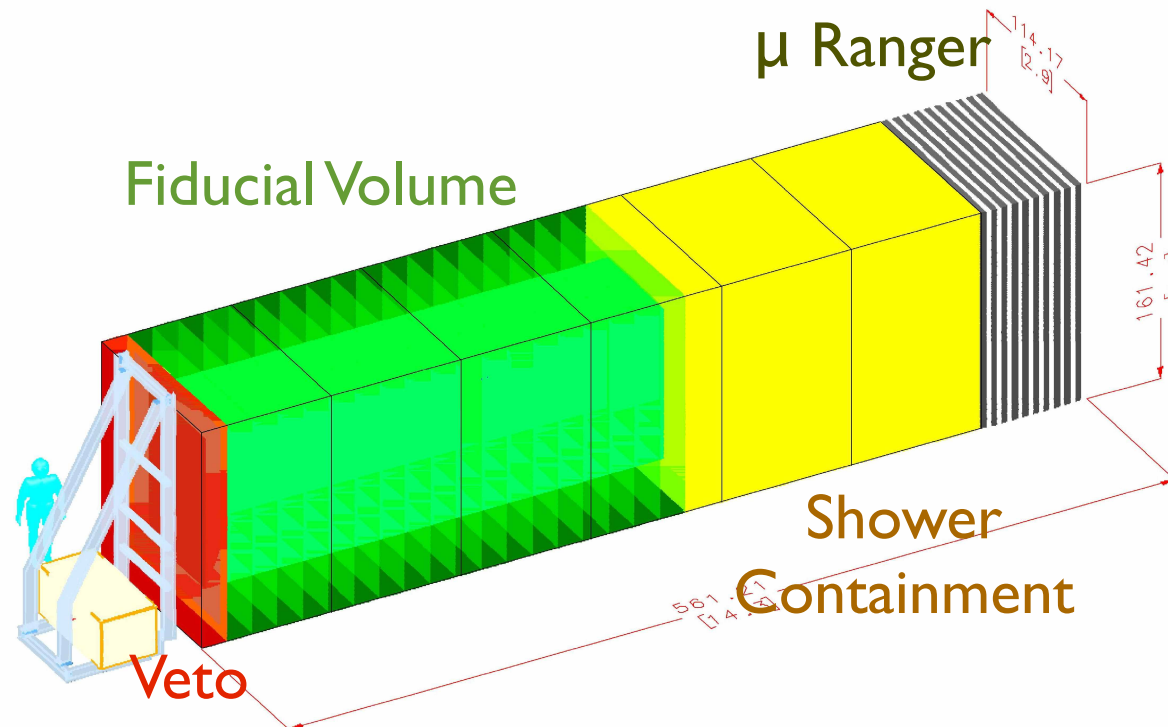
- 14 kt total mass, 70% scintillator
- 930 planes
- ~3 m equivalent earth overburden of barite and concrete



# Near Detector

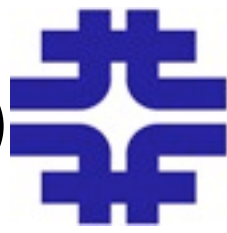


- Same extrusions, scintillator and readout as FD
- Located upstream of MINOS ND, 14 mrad off axis
- 210 t total mass, 20 t fiducial
- Steel muon catcher at back, contains up to 2 GeV muons





# Near Detector - on the Surface (NDOS)

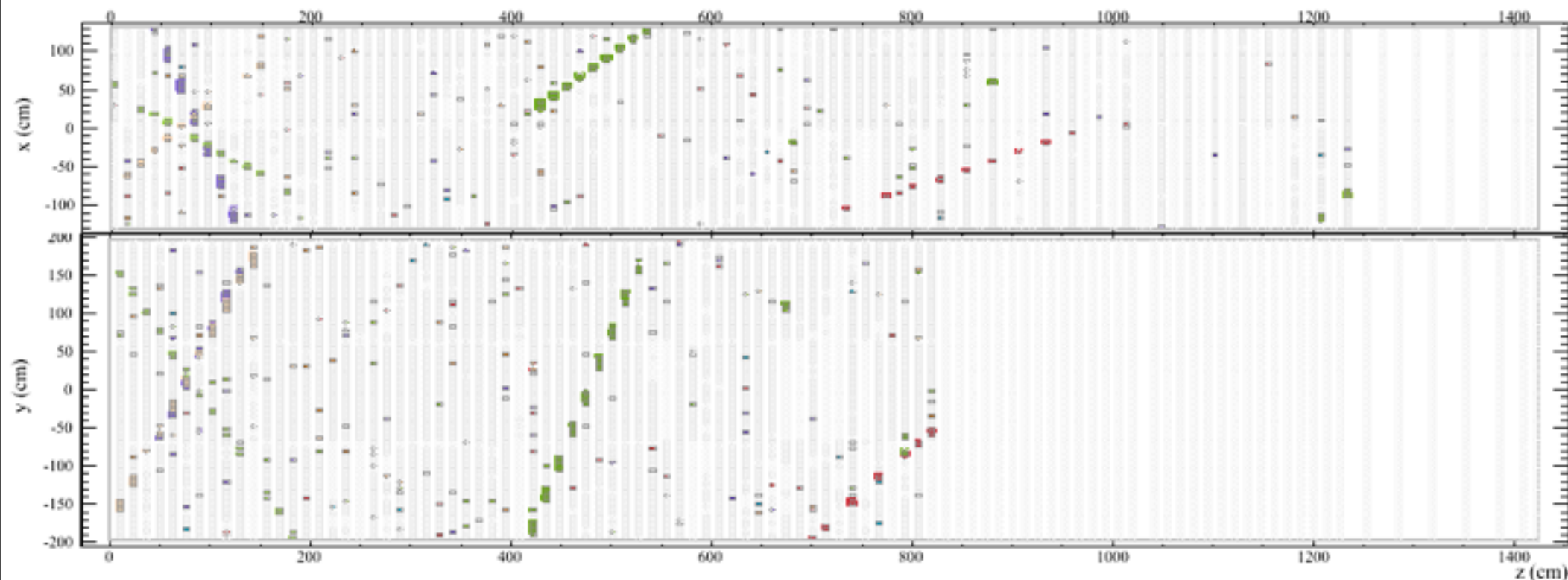


- ND constructed on surface late summer 2010
- Test of construction and integration
- Sees very off-axis NuMI beam (107 mrad) and on axis Booster beam
- Take data parasitically during MINOS and MINERvA running





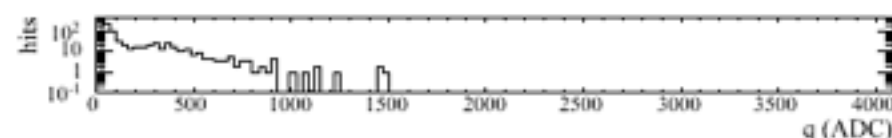
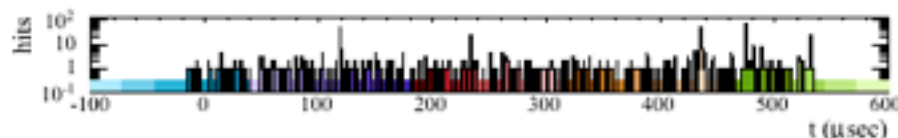
# Cosmic Ray in NDOS!



NOVA - FNAL E929

Run: 11945/B  
Event: 309631

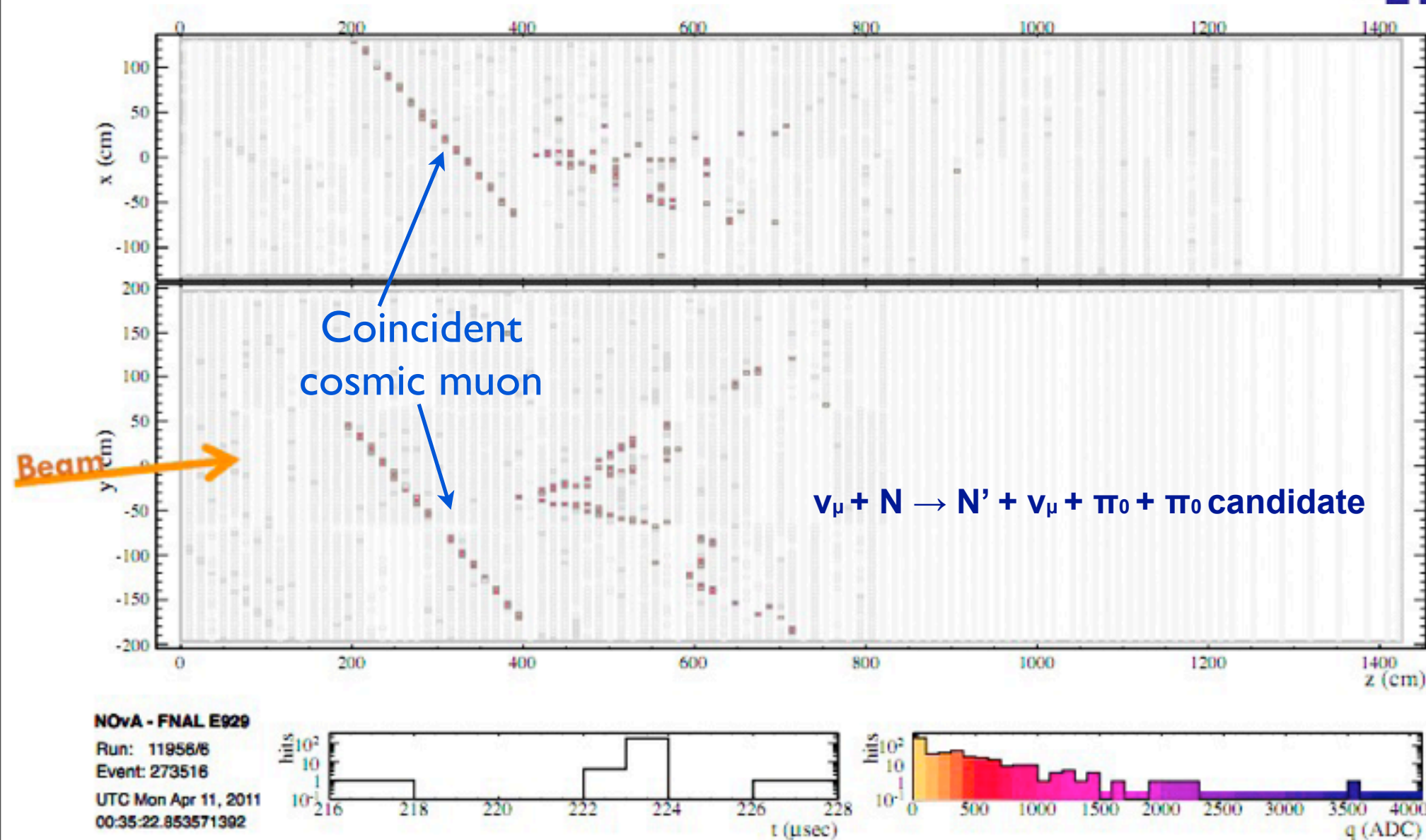
UTC Sat Apr 9, 2011  
04:35:37.133364000



- Color shows time
- Hits scaled by charge
- Detector is not fully instrumented due to problems with APD installation



# Neutrinos in NDOS!



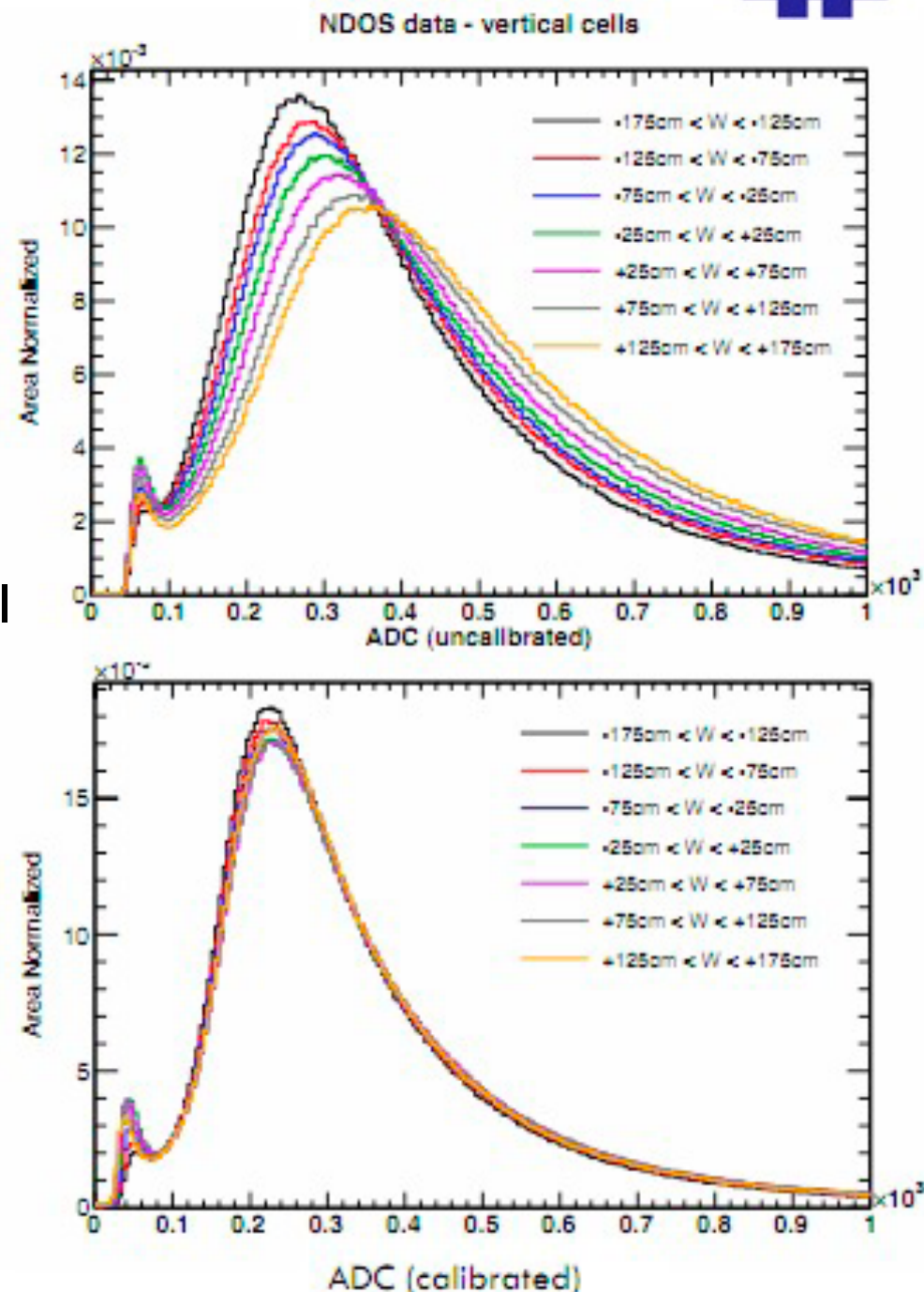
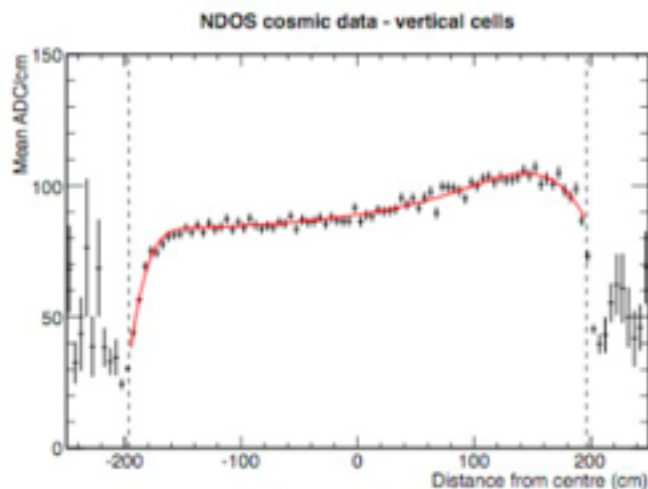
- Have observed neutrinos from both NuMI and Booster neutrino beams



# Calibration



- Use cosmic muons as inter-detector calibration source
- Top plot shows response for different muons passing through a single cell in different locations
- Bottom shows attenuation corrected responses
- Below is measured attenuation in same cell
- NDOS has been very valuable in testing these procedures





# Schedule



- NDOS running since October, 2010
- FD construction at Ash River site begins January, 2012, finished in early 2014
- Accelerator shutdown March, 2012
- 700 kW beam turns on February, 2013, 2/3 FD built
- ND cavern excavation during accelerator shutdown

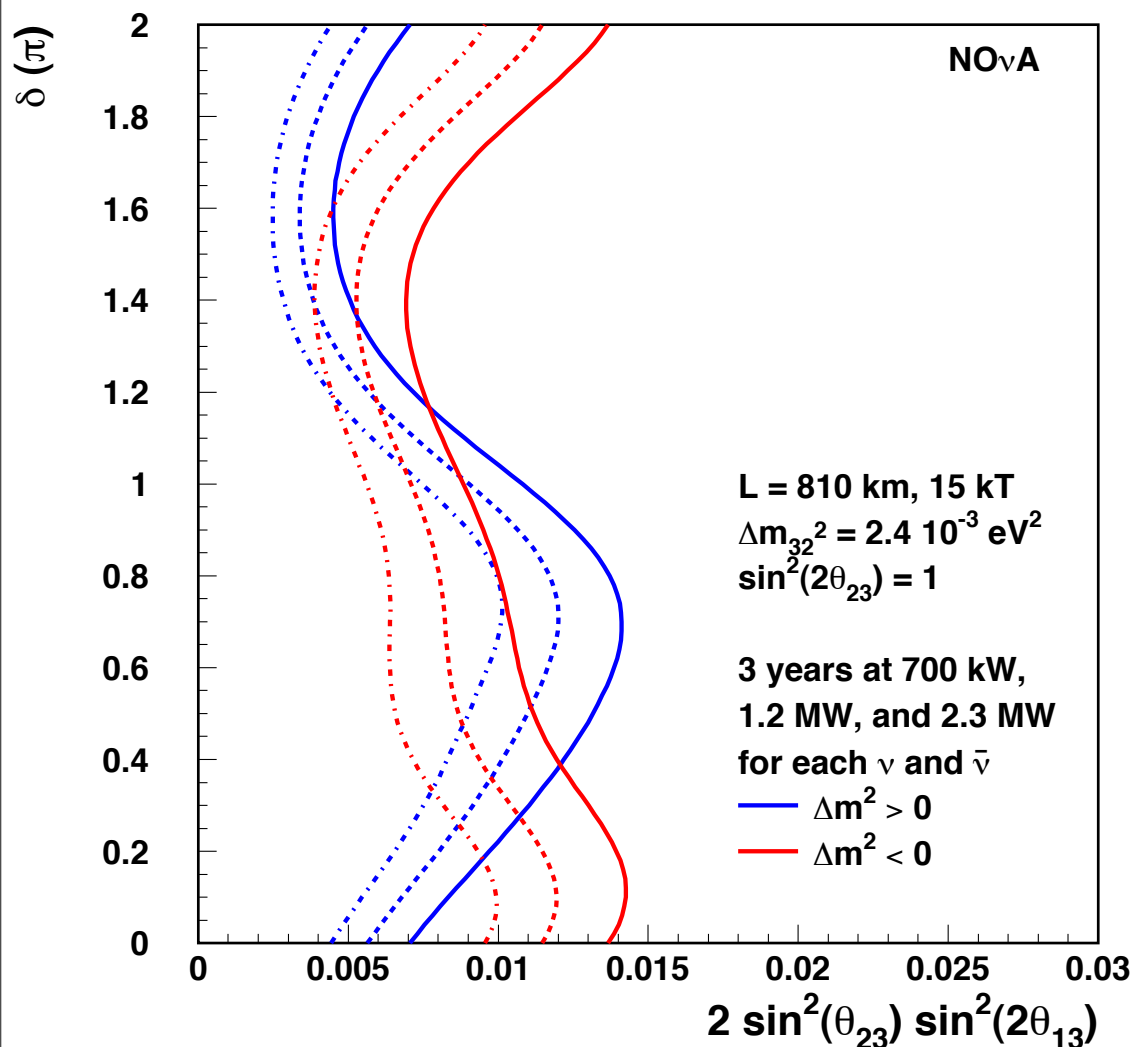


Entrance to Far Detector Lab



# Sensitivity to $\sin^2(2\theta_{13})$

90% CL Sensitivity to  $\sin^2(2\theta_{13}) \neq 0$

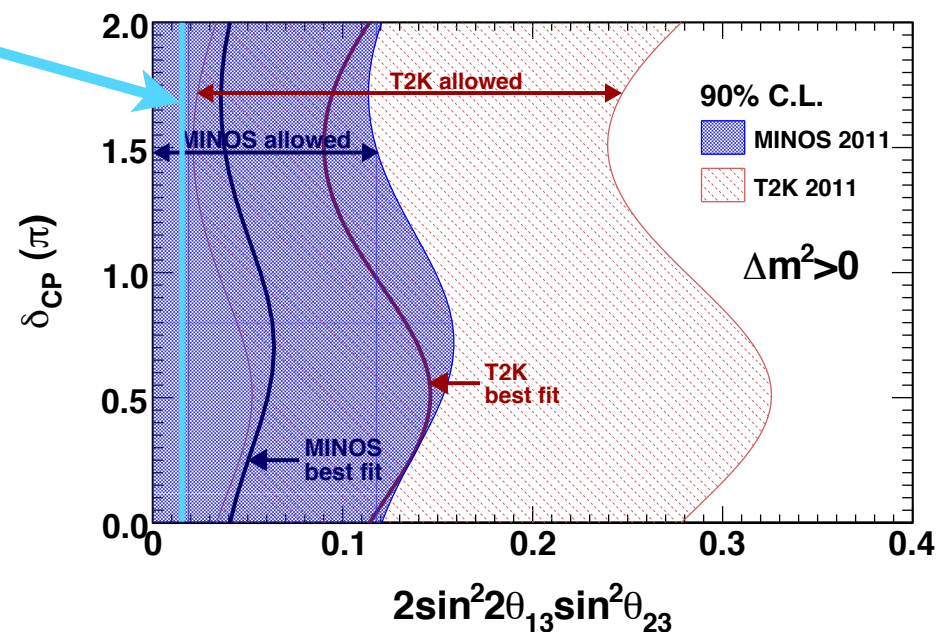
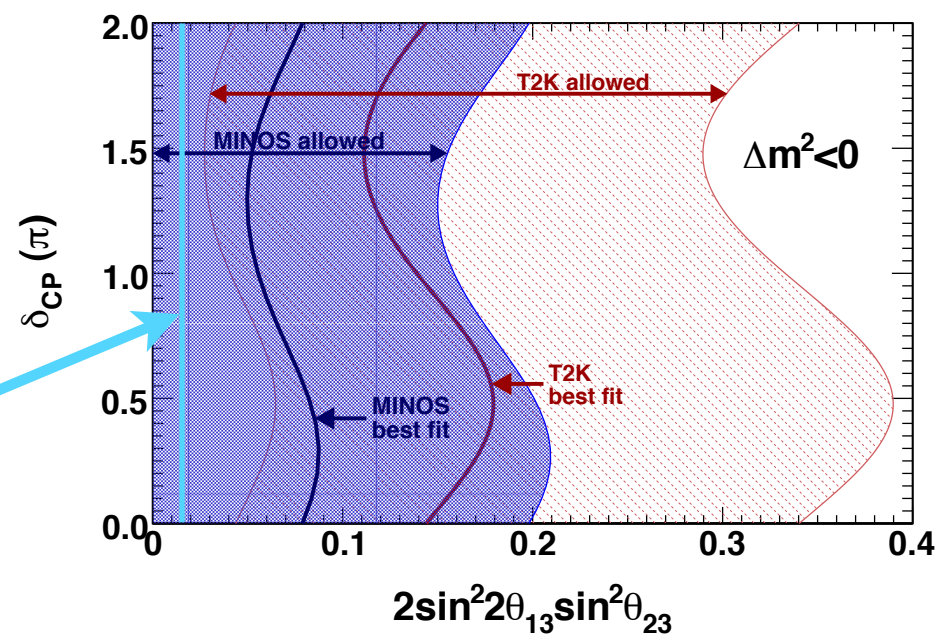
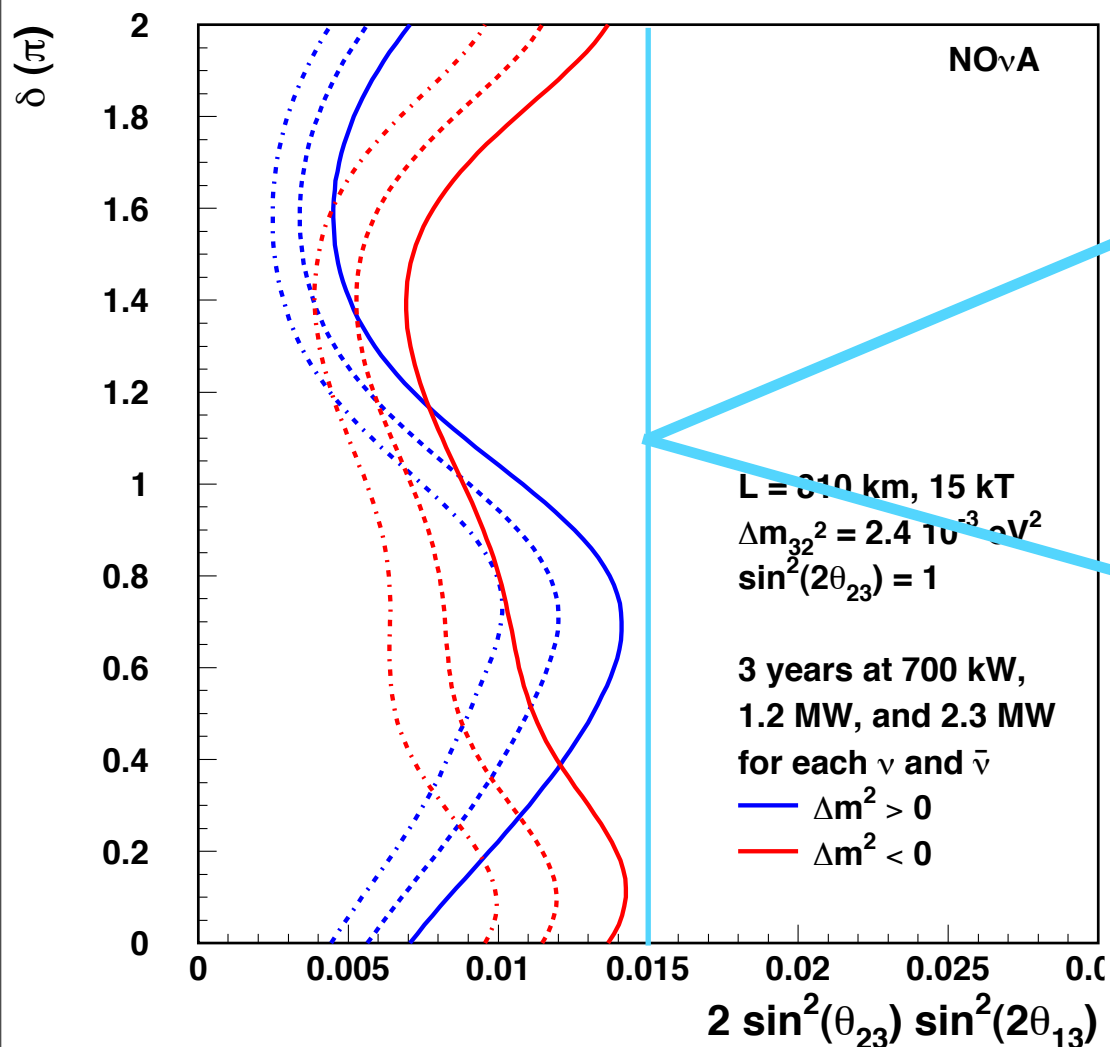


- Plot shows  $\delta$  vs  $\sin^2(2\theta_{13})$  90% CL sensitivity for 3 years each of neutrinos and anti-neutrinos
  - 700 kW - solid lines
  - 1.2 MW - dashed lines
  - 2.3 MW - dash-dot lines
  - Normal hierarchy - blue
  - Inverted hierarchy - red
- Curves are equal oscillation probability curves
- Sensitivity varies based on mass hierarchy



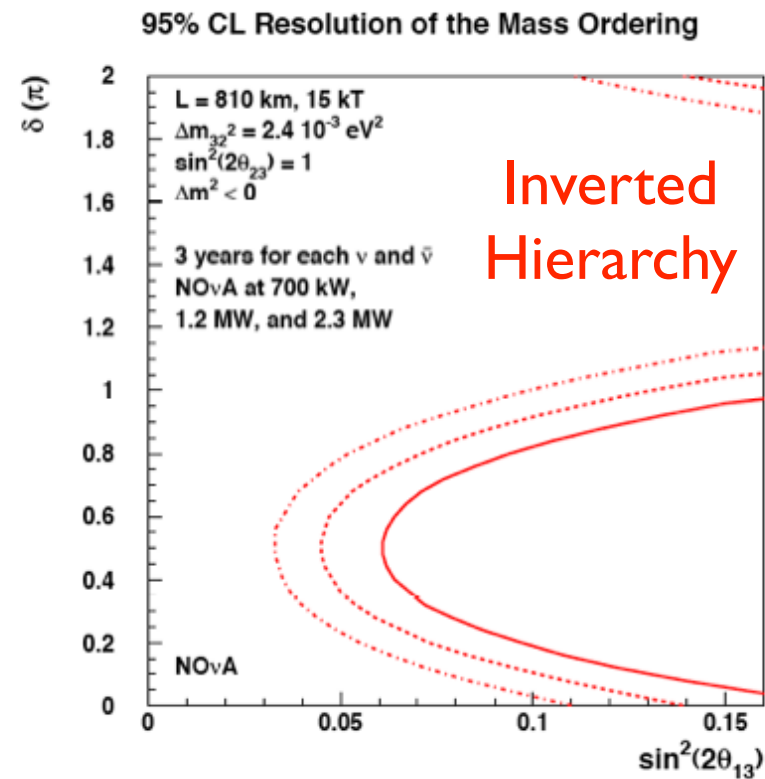
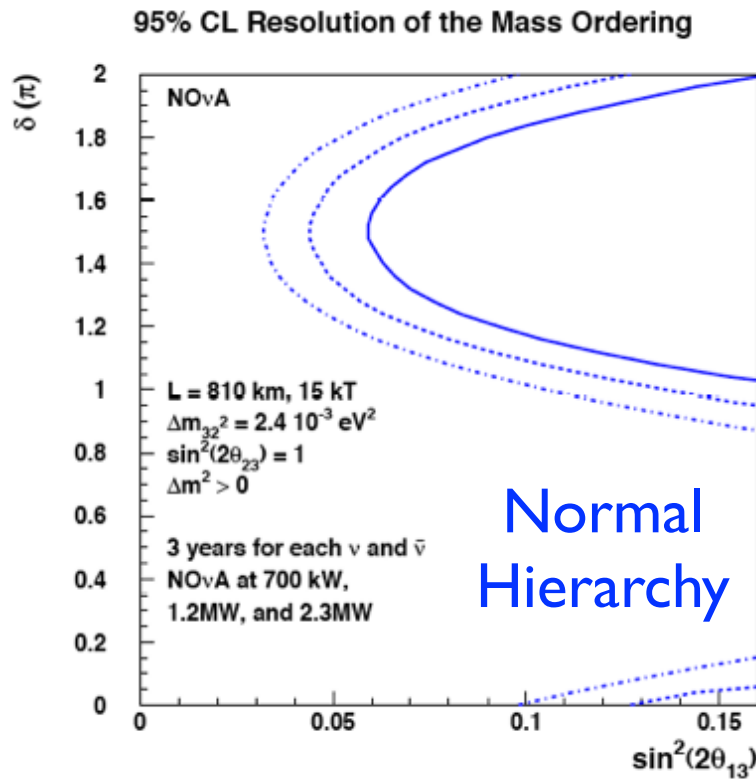
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# Sensitivity to Mass Ordering

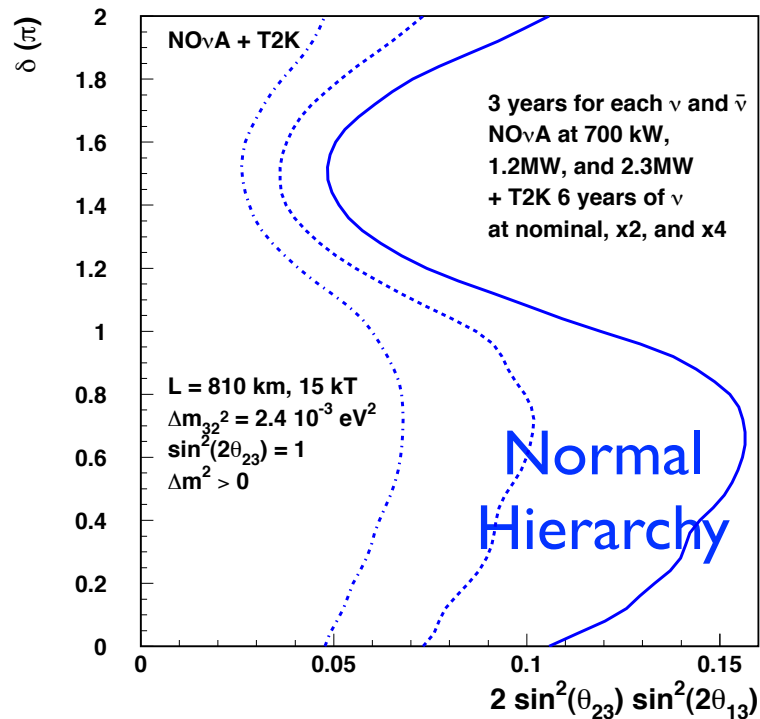


- 95% CL resolution for mass ordering shown for **normal** and **inverted** hierarchy, curves represent different beam powers
- Even better resolution with information from another baseline
- Resolve ambiguity for values of  $\sin^2(2\theta_{13})$  to the right of the curves

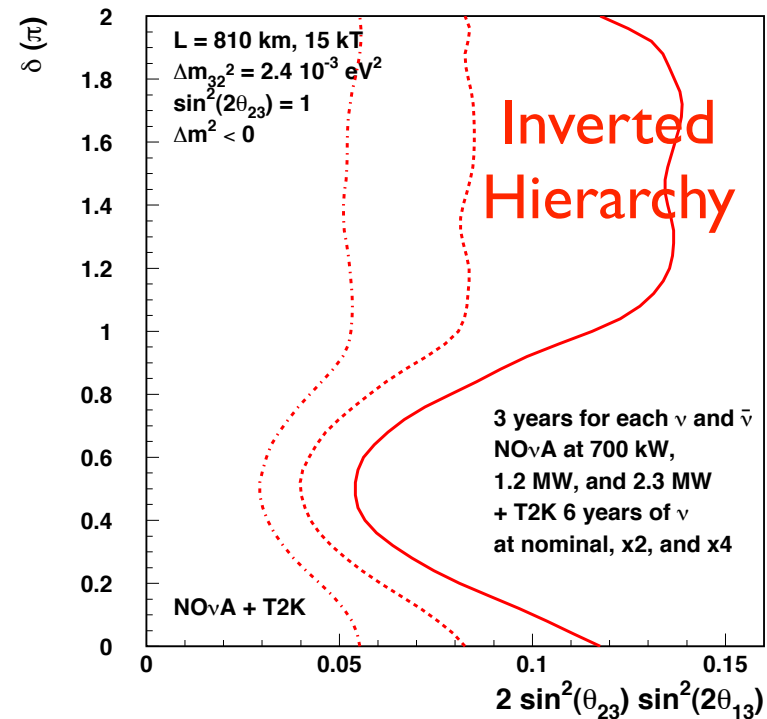


# Sensitivity to Mass Ordering

95% CL Resolution of the Mass Ordering



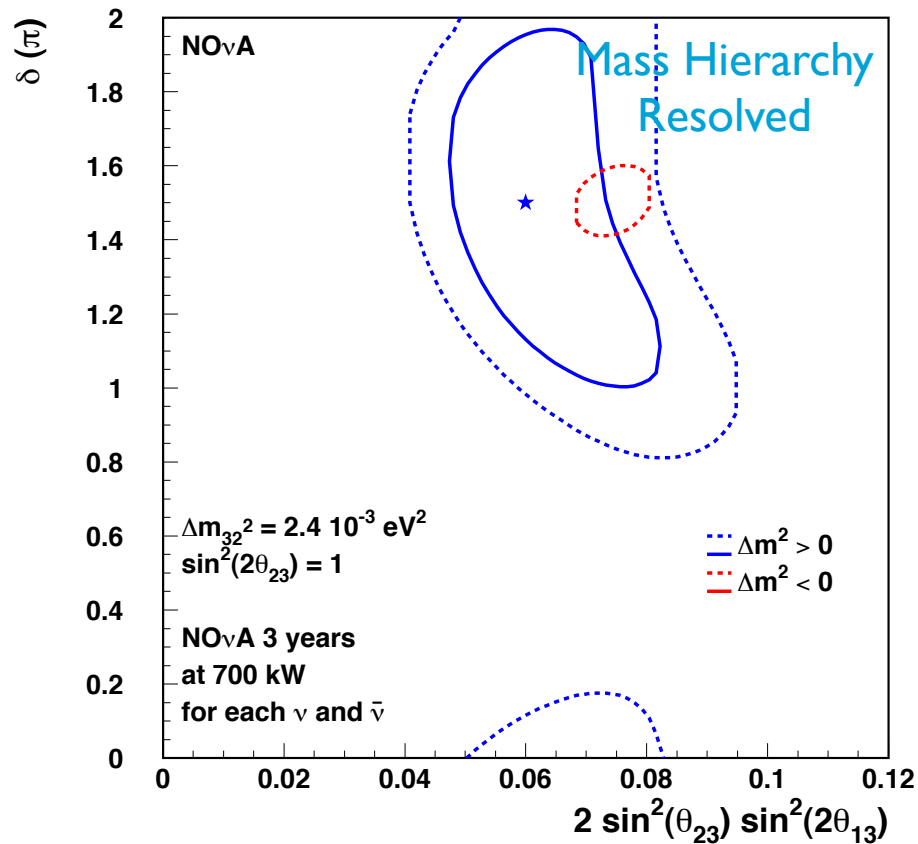
95% CL Resolution of the Mass Ordering



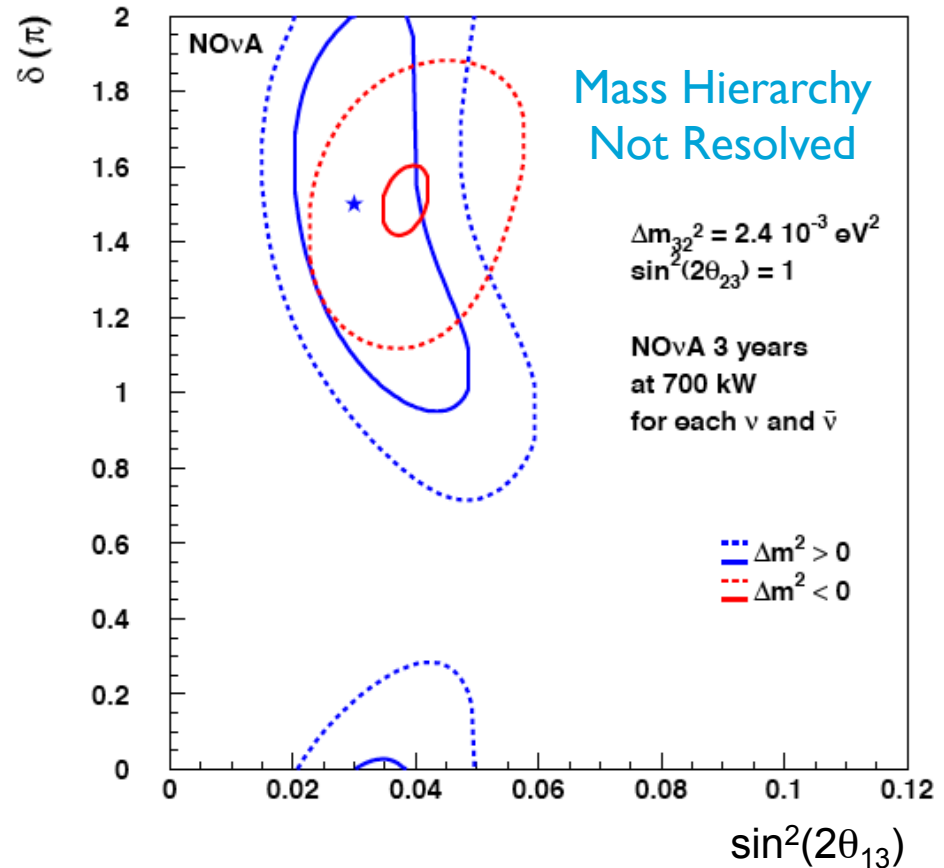
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# Sensitivity to CP Violating Phase $\delta$

Contours for Starred Point for NOvA



1 and 2  $\sigma$  Contours for Starred Point for NOvA



- Plots show 1 and 2 $\sigma$  contours for 700 kW beam with chosen point
- NOvA sensitivity includes  $\delta = 0, \pi$  at 2 $\sigma$
- Can point to which CP phase half plane to target for future measurement



# Conclusions



- NOVA poised to answer several important questions about neutrino oscillations
  - Search for  $\nu_{\mu} \rightarrow \nu_e$  oscillations, measurement of  $\theta_{13}$
  - Determination of mass hierarchy
  - Search for CP violating phase
  - Precision measurement of  $\theta_{23}$
  - Clarification of interesting new results from MINOS
- NDOS is taking cosmic ray and (anti-)neutrino data, important prototype for construction of FD, providing valuable lessons for construction and analysis
- 14 kt far detector on schedule to be completed in 2014





# What We Know About Oscillations



- A variety of experiments (solar, reactor, atmospheric) have shown us

- $\text{Atm} \rightarrow \Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$
- $\text{Solar} \rightarrow \Delta m^2 \approx 8 \times 10^{-5} \text{ eV}^2$  (mass)<sup>2</sup>

- Figure shows the fraction of flavor states in each mass state
- Most mixing angles are large
- Zero point of mass scale currently unknown

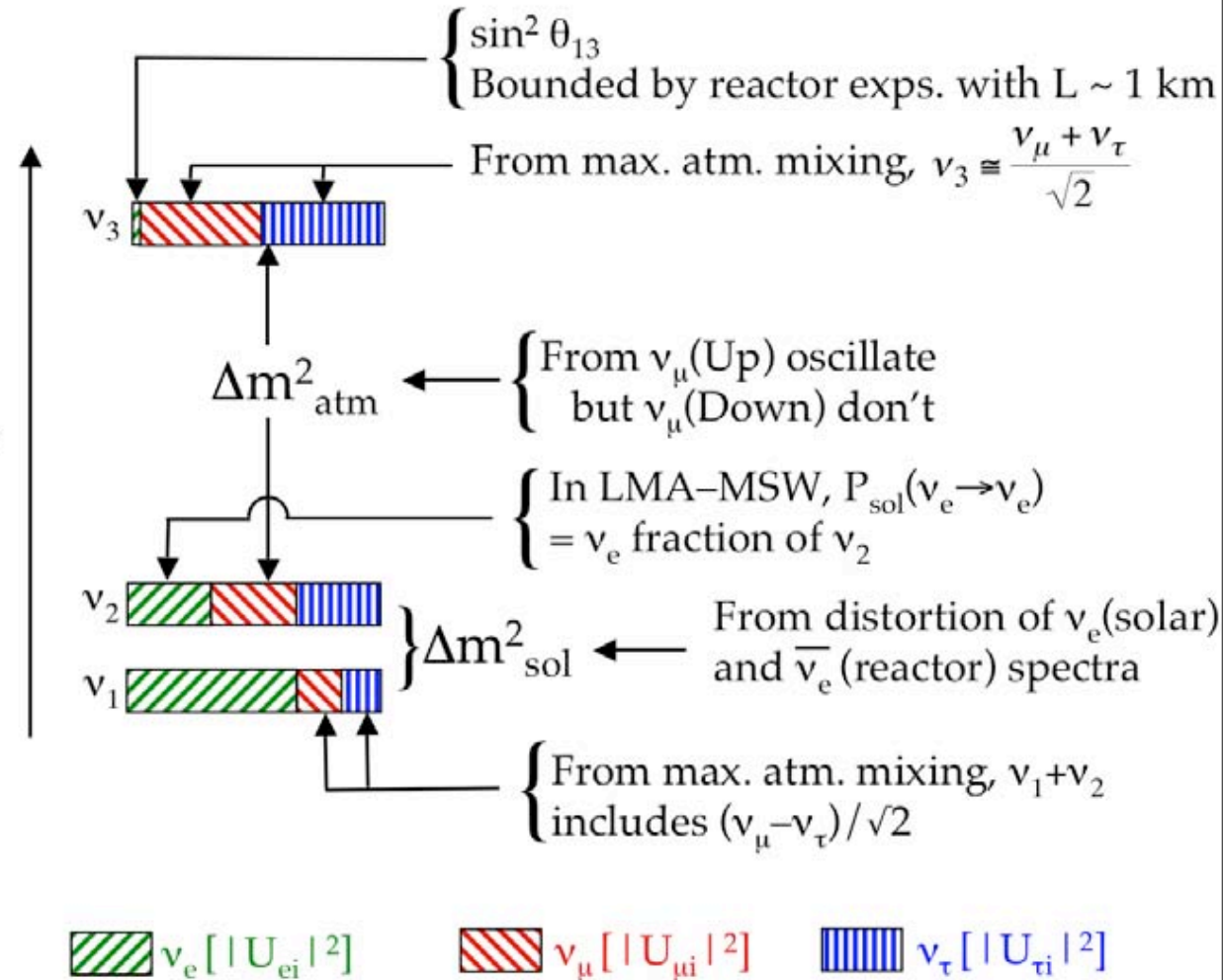
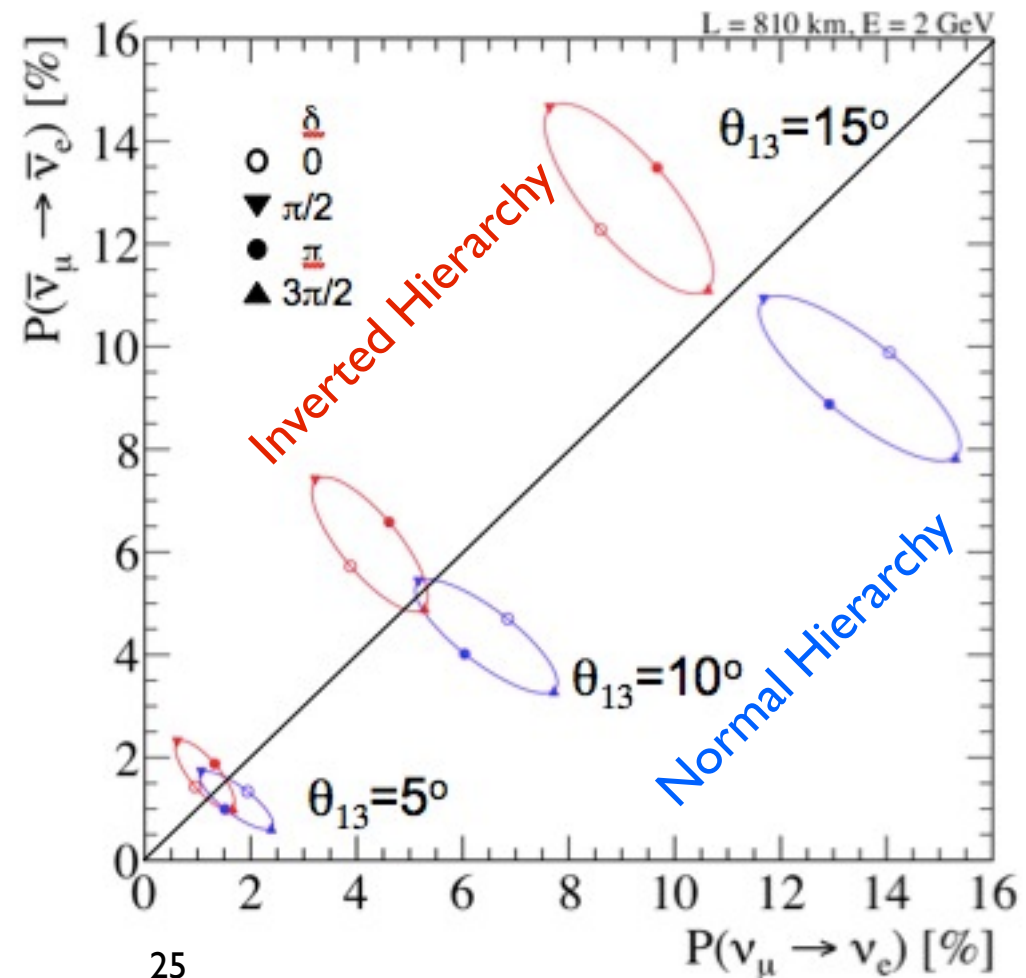
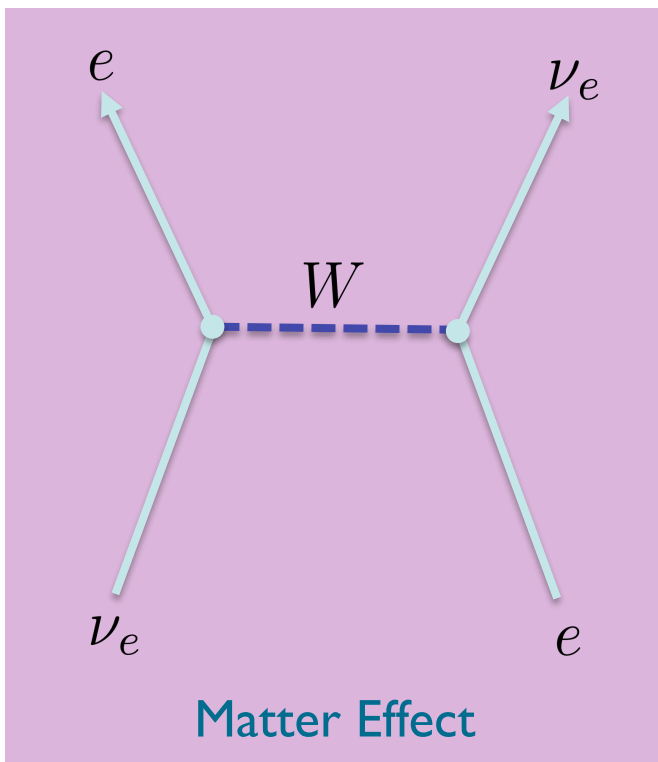


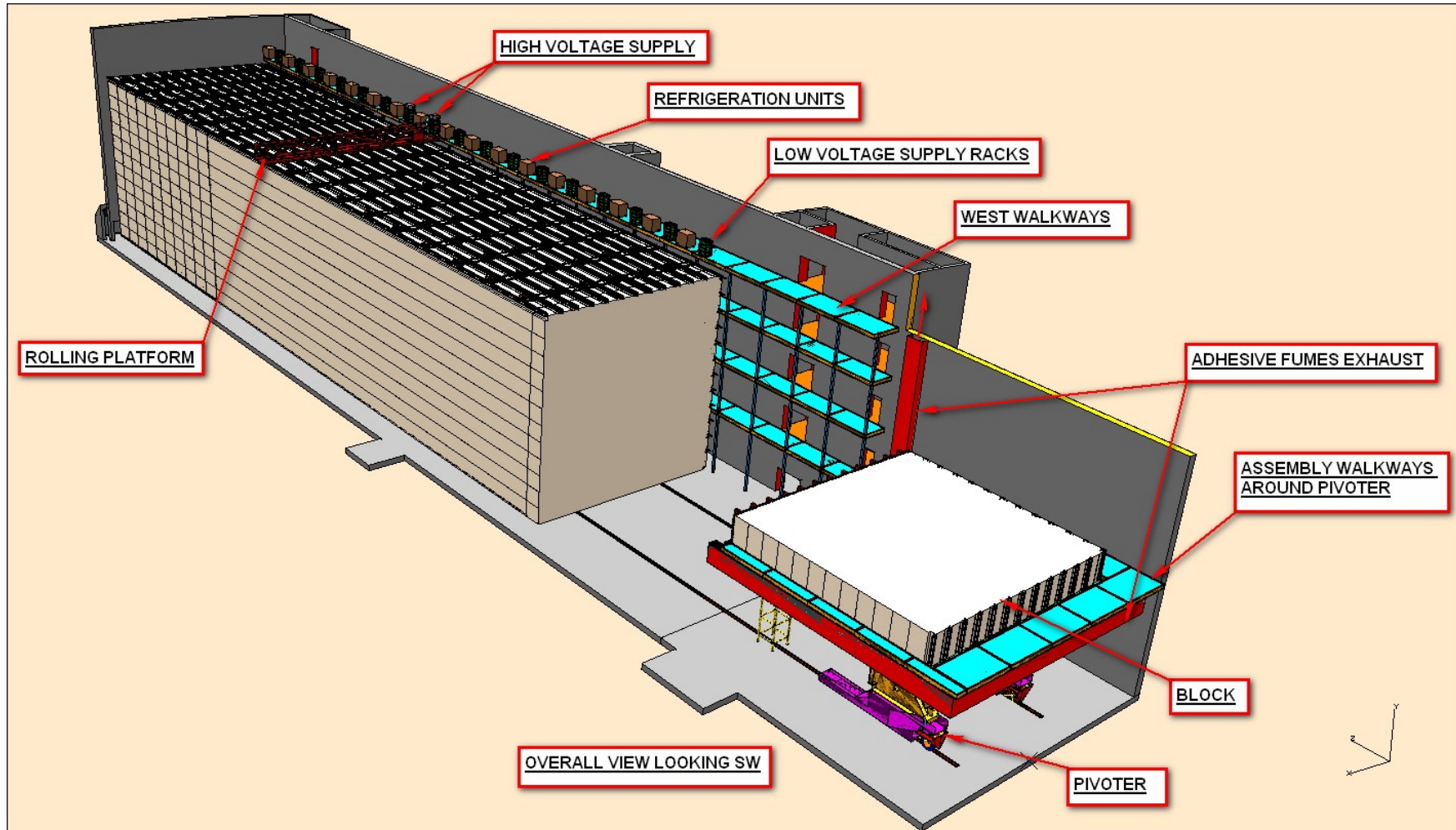
Figure from B. Kayser (2004)



# Measuring $\nu_\mu \rightarrow \nu_e$

- It's hard - subdominant oscillation mode so it is a rare process
- Need large detectors and powerful beams to observe it
- Matter effects and CP violation can help clarify some of these questions if  $\theta_{13}$  is large enough





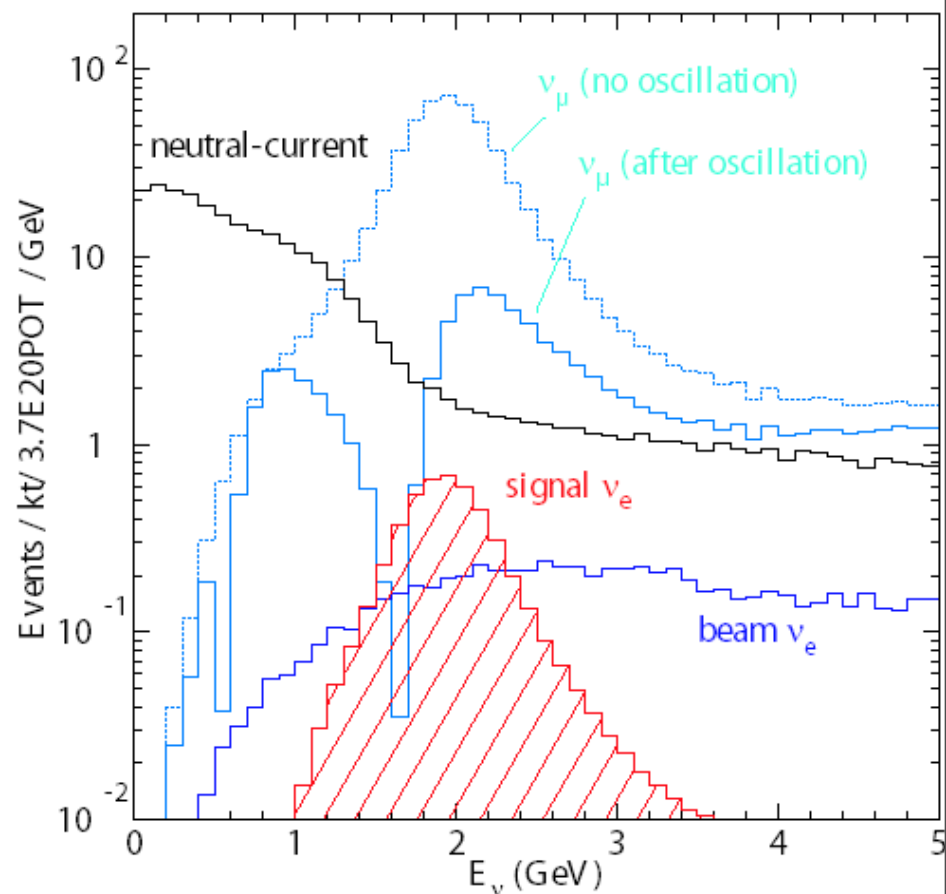
- Built in blocks of 31 planes assembled horizontally and then raised to vertical
- Filled in situ



# Expected Spectrum at Far Detector

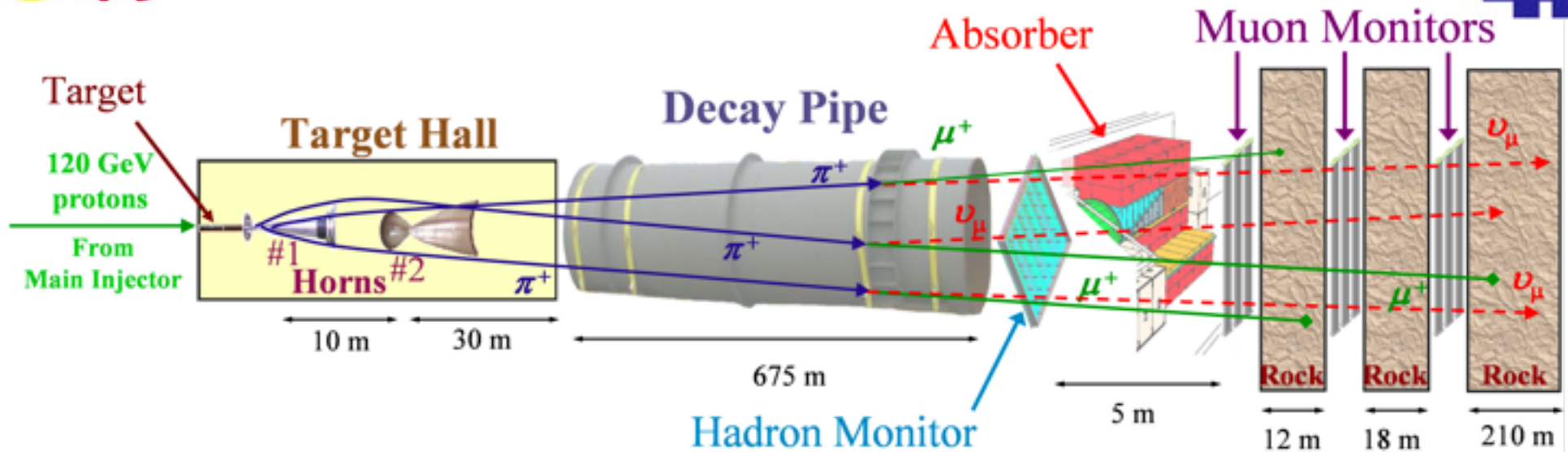


- Spectra assume  $|\Delta m_{32}^2| = 2.5 \times 10^{-3} \text{ eV}^2$ ,  $\sin^2(2\theta_{13}) = 0.01$
- $\nu_\mu$  CC background reduced by oscillations, generally easy to distinguish muons from electrons
- NC background harder to reduce, but majority at lower visible energy than the signal
- Beam  $\nu_e$  spectrum is more or less flat
- Detector designed to maximize separation of hadronic and EM showers - low Z, fine grained sampling compared to radiation length





# NuMI Beam



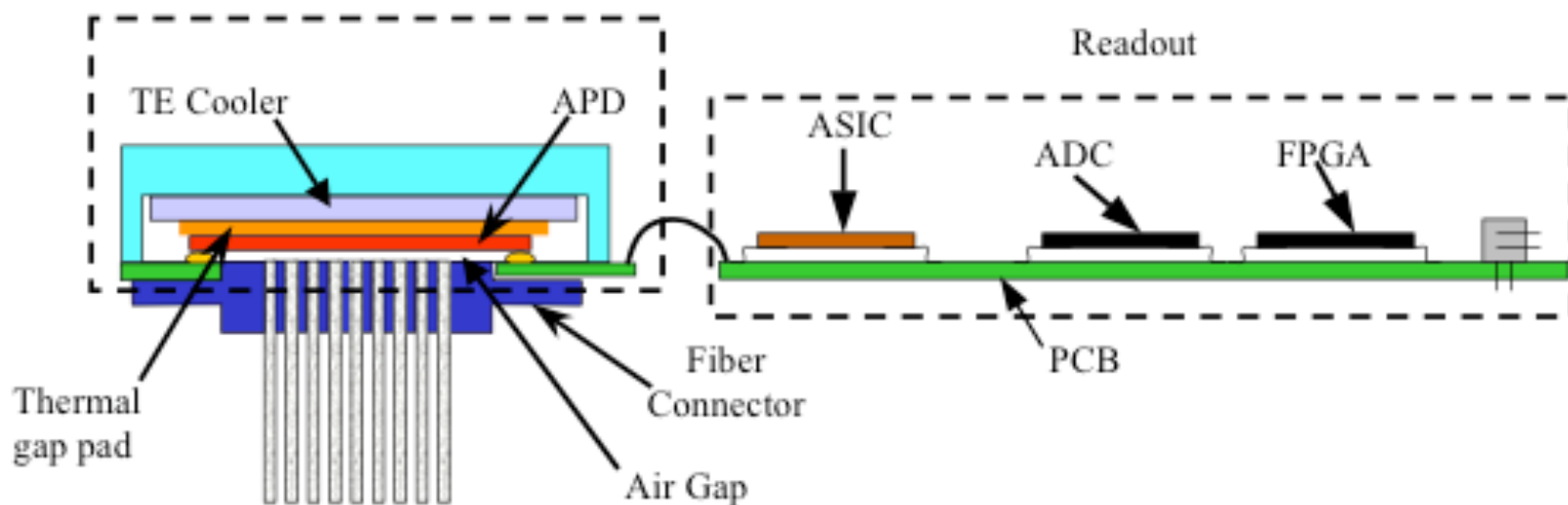
- Magnetic horns focus produced pions and kaons, pions and kaons decay into muons and neutrinos - can select neutrinos or anti-neutrinos using horn current
- 10  $\mu$ s beam spill, every 2.2 seconds
- Operating since 2005, currently delivers 280 - 300 kW
- Recent experiments operating in the beam are MINOS, MINERvA, and ArgoNeuT



# Readout

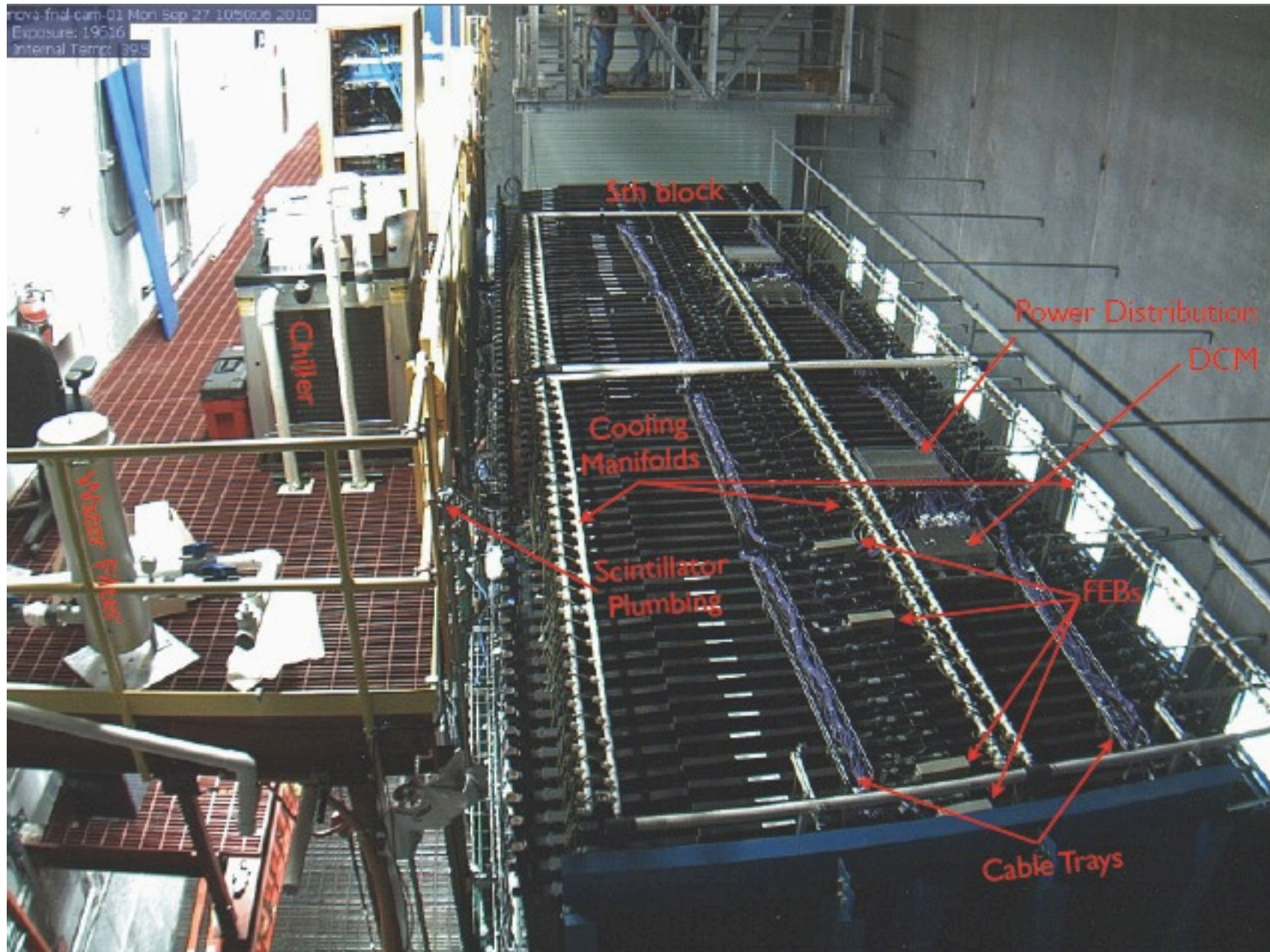


APD Module - 32 channels

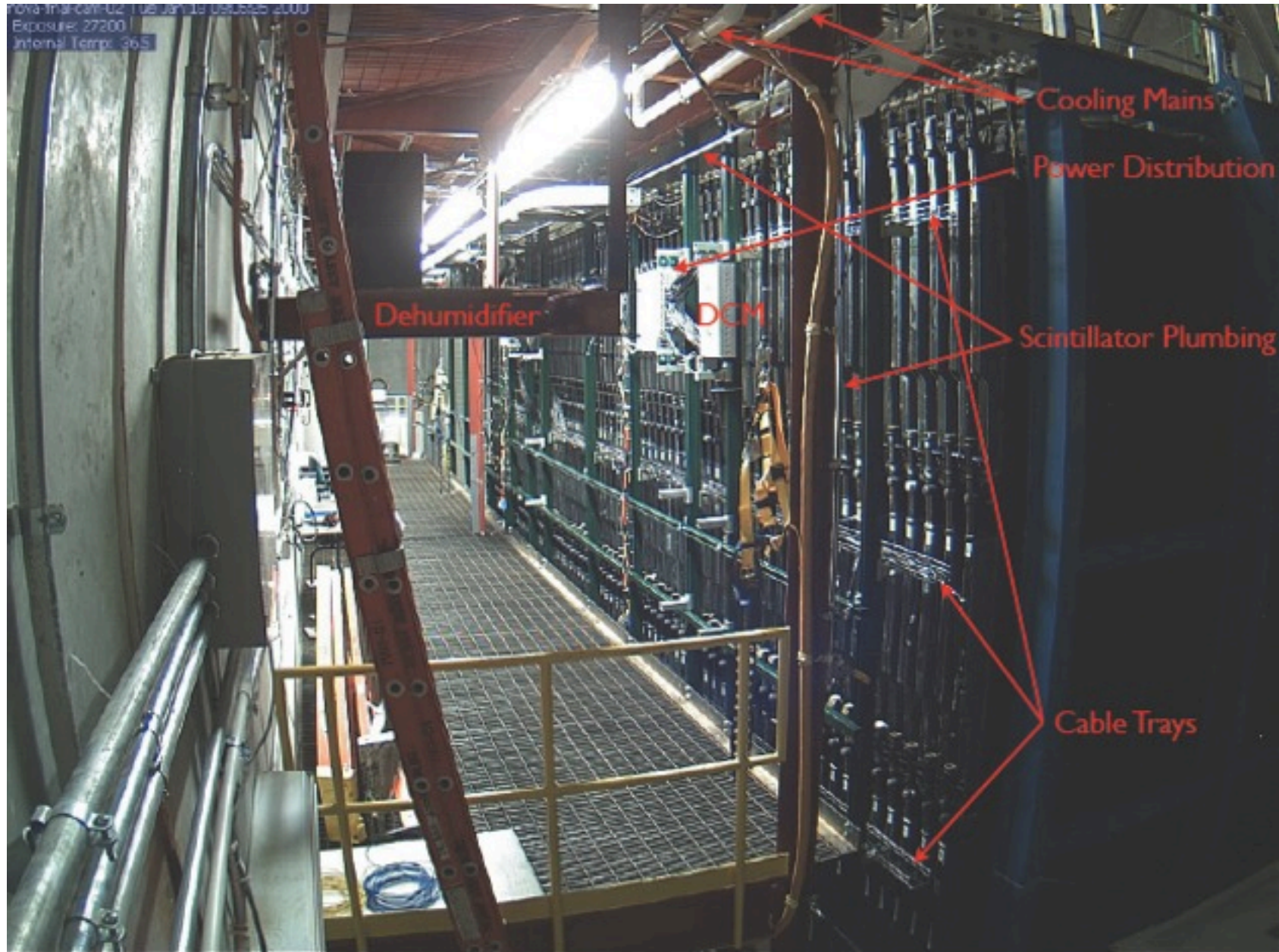


- Avalanche Photo Diodes used to detect scintillation light
  - 85% Quantum efficiency, 100x Gain
  - Cooled to -15 C to reduce dark noise to 2 PE, 4PE total noise
- ASIC handles amplification, shaping and multiplexing to ADC

# Near Detector - on the Surface

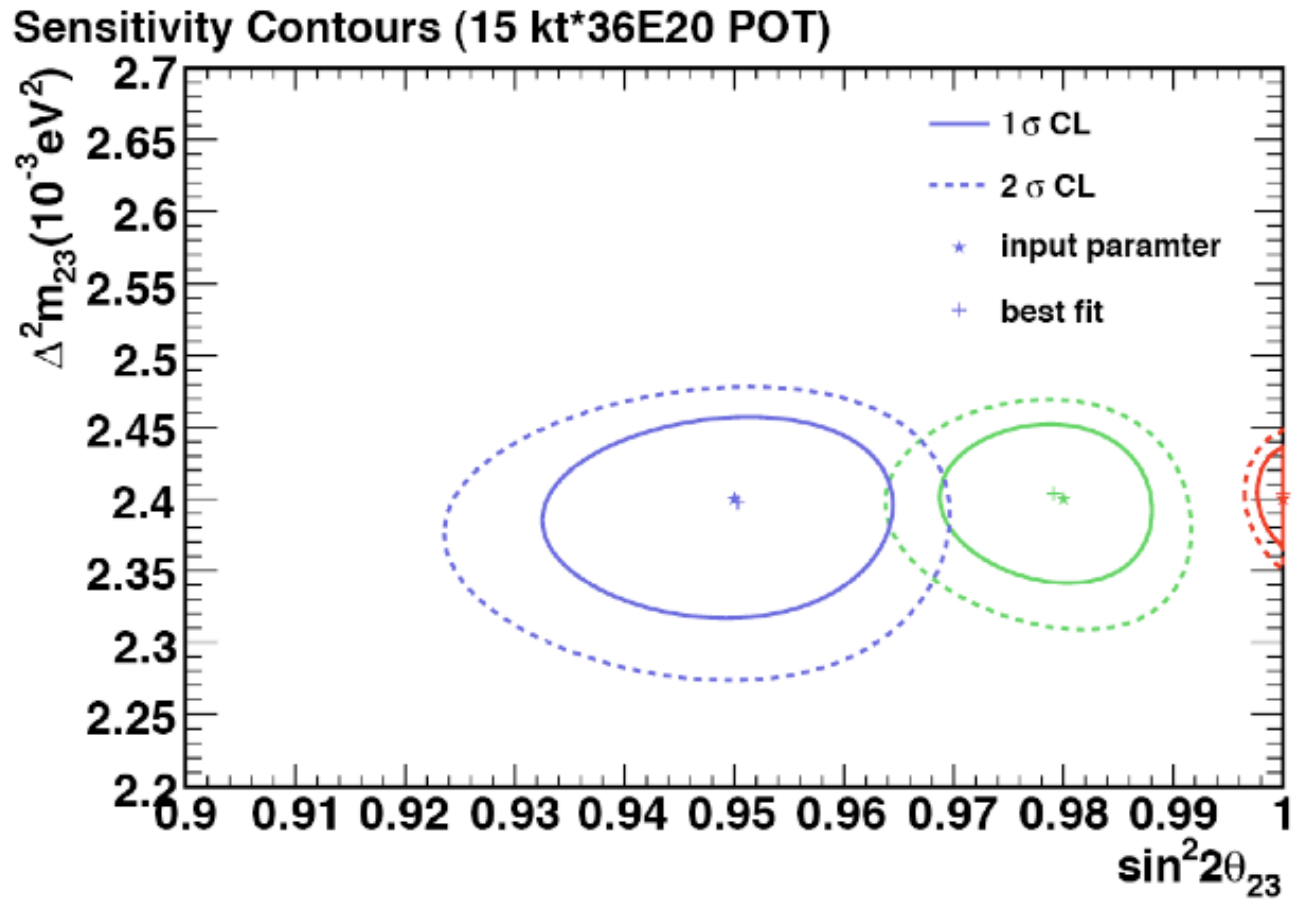


# Near Detector - on the Surface





# Measurement of $\sin^2(2\theta_{23})$



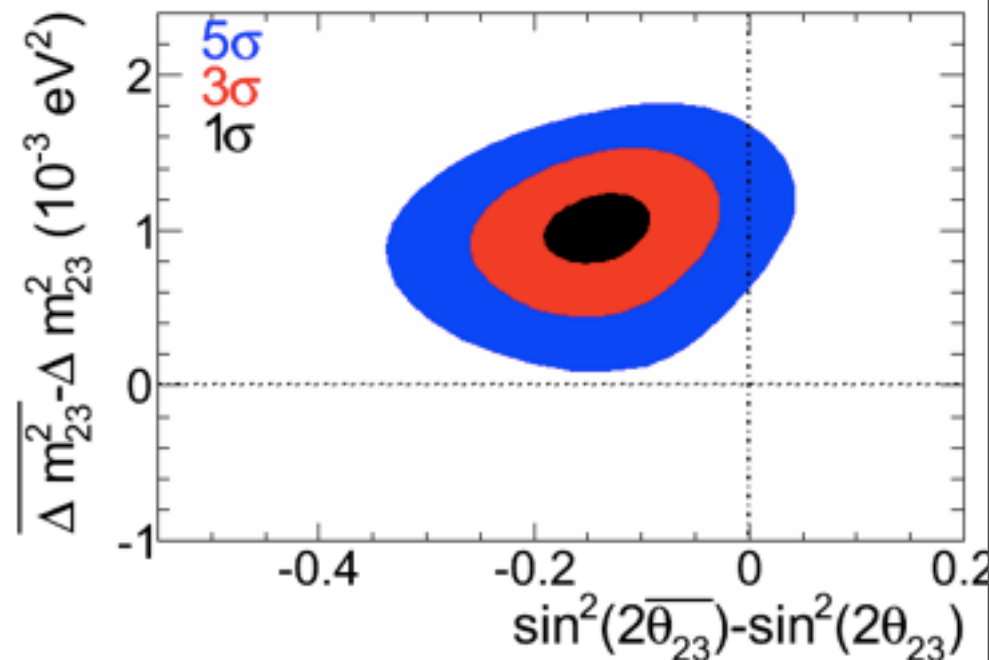
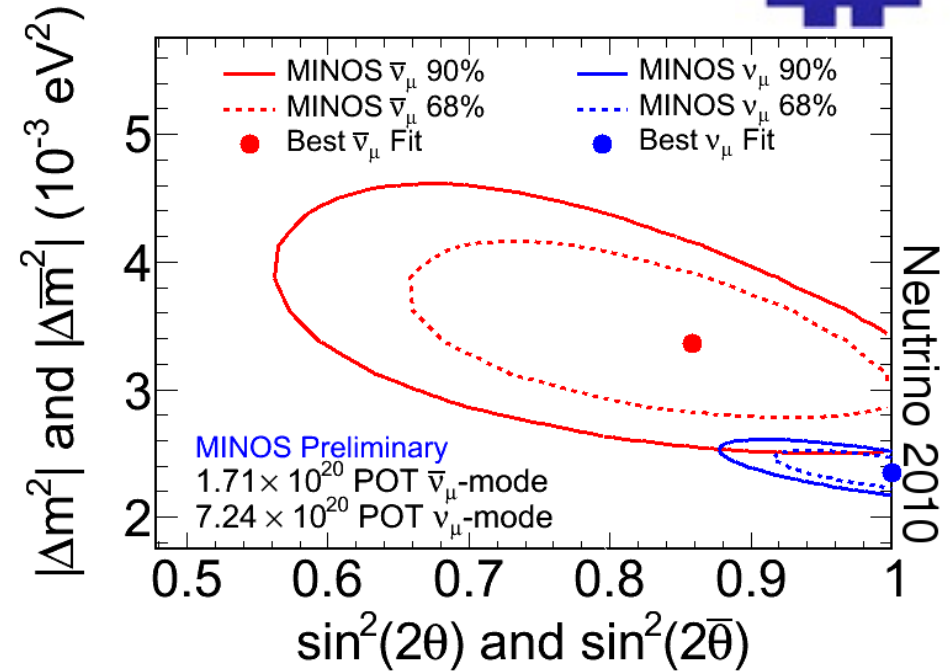
- Quasi-elastic  $\nu_\mu$  charged current interactions provide channel to make high precision measurement
- Possible due to excellent energy resolution, narrow band beam



# $\nu_\mu$ vs $\bar{\nu}_\mu$ Disappearance

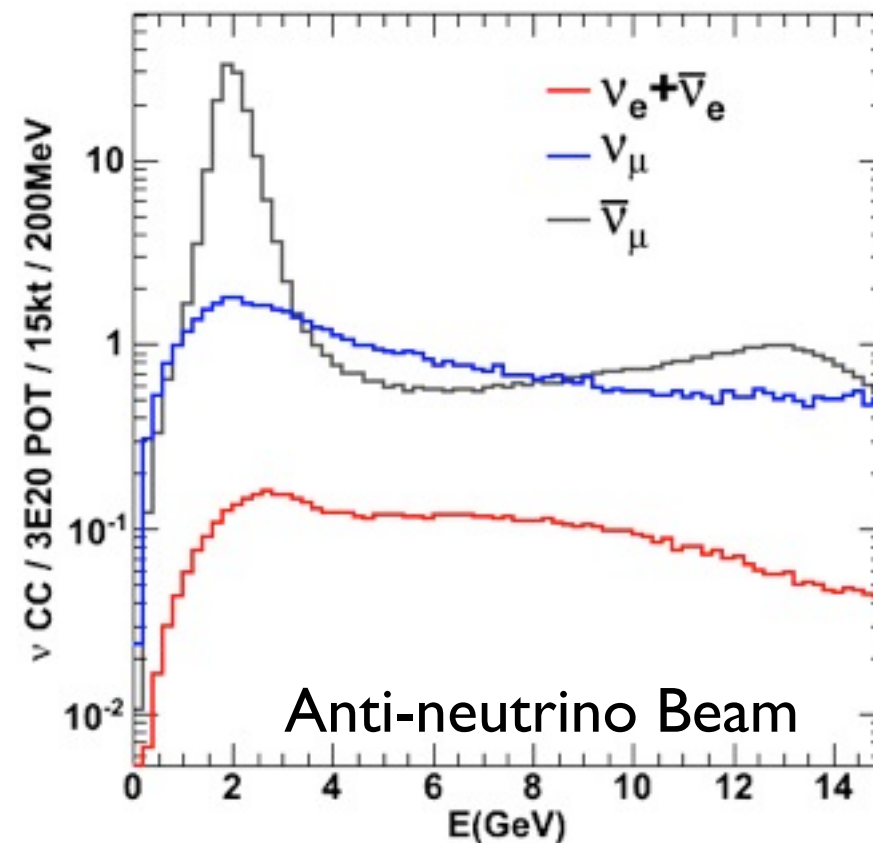
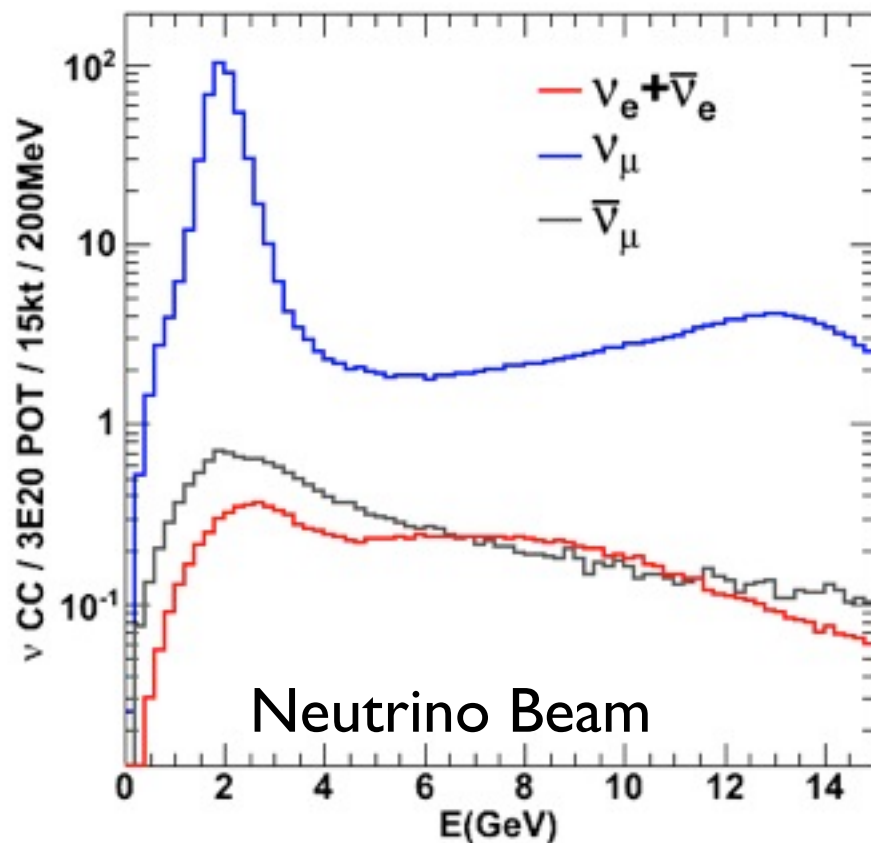


- MINOS showed tension between neutrino and anti-neutrino oscillation parameters for  $\nu_\mu \rightarrow \nu_\tau$
- NOVA can measure a difference between the two scenarios to  $3\sigma$
- Assumes MINOS measured values are correct





# Sensitivities



- Following plots are all for 15 kt detector
- 3 years each of neutrino and anti-neutrino beams, 0.7, 1.2, and 2.3 MW powers
- Full simulation of flux, interactions, and detector response
- Reconstruction based event selection